Cover

L Division has developed a new, high-power 100-fs laser to study solid-density plasmas. A colliding-pulse mode-locked (CPM) dye laser is used to generate the initial laser pulses. The photograph shows the saturable absorber dye jet that mode-locks the laser to provide pulsed operation from a continuous-wave pumped laser cavity. The saturable absorber consists of a 30- to 50- μm -thick jet of DODCI dye dissolved in ethylene glycol. The solution is pumped through the nozzle at the top of the photograph and collected in the funnel at the bottom.

The jet is enclosed by two concave mirrors, forming a subresonator that focuses the intercavity beam on the jet. Shown is the 620-nm wavelength intercavity beam of the CPM laser. This beam is then amplified in a series of dye and titanium sapphire amplifiers to produce 100-fs pulses with 1 J of energy.

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NUCLEAR TEST- EXPERIMENTAL SCIENCE

Annual Report
Fiscal Year 1989

*Lawrence Livermore
National Laboratory*

University of California
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Nuclear Test- Experimental Science

Overview

Fiscal year 1989 was one of outstanding accomplishments for the Nuclear Test-Experimental Science (NTES) Program at Lawrence Livermore National Laboratory (LLNL). It was the first complete year of our revitalization of nuclear testing and the experimental science that underlies it through commitment to enhanced science, enhanced efficiency, and enhanced quality.

Enhanced Science. Many measures of our progress in enhancing the scientific achievements of the NTES Program are evident. In FY 1989, we hired two dozen scientists to address the experimental challenges that face the nuclear weapons program. These people add to a core of innovative and highly experienced weapons experimentalists who provide a unique capability to the nation—one that is unrivaled in the world of experimental physics and nuclear chemistry. Our technical staff also provided the expertise to develop new measurement techniques that

were fielded on underground nuclear tests. These techniques are essential to understanding the science of nuclear weapons. They represent the forefront of experimental atomic and nuclear physics and, of necessity, exceed the capabilities of the best university laboratories.

The NTES Program continues to improve its world-class experimental facilities, which are necessary to remain at the leading edge of weapons-related experimental science. For example, in FY 1989, we completed the electron-beam ion trap (EBIT) facility, which produces highly ionized atomic species and is used to solve unique weapons physics problems. In addition, we completed the preliminary stages of a femtosecond laser facility for generating weapons-like dense plasmas in matter and demonstrated a new electron spectrometer, which among other applications, will soon provide the world's most sensitive measurement of the upper limit on the mass of the neutrino.

Enhanced Efficiency. We also made considerable progress in improving the efficiency of NTES operations. We more than doubled our capacity for data return from underground nuclear tests by judiciously implementing new recording technology, such as electro-optics and photonics, and the potential exists for future increases of an order of magnitude or more. Operational efficiencies also were implemented to benefit the Program. One example is the development of an integrated calibration capability (for the Janus laser system) that decreases the effort to calibrate instruments and increases the quality of the calibrations.

We also achieved several operational efficiencies in our activities at the Nevada Test Site (NTS) in FY 1989. For example, we consolidated contractor construction support, drilling, and engineering operations with those of Los Alamos National Laboratory. In addition, we redesigned the emplacement operations for special measurement cables, modified hole-stemming plans to use cheaper materials, standardized diagnostic components where possible, and reconfigured the Nuclear Test Operations Department, our field support organization. Total FY 1989 productivity gains from these efforts approached 15%.

Enhanced Quality. The NTES Program has a tradition of striving for the highest standards in safety and in the quality of our operations. Nevertheless, our goals are still higher, and our accomplishments in FY 1989 enhanced our level of quality throughout the Program. A major example was our fielding of the Contact Event, the most sophisticated and complex underground weapons test ever conducted.

This experiment returned 100% of more than 3000 channels of data (more than a factor of 2 greater than the previous record) with no measurement failures. In addition, the quality of these data exceeded that of previous underground test data, although the instruments are much more sensitive to background noise and the complex diagnostics canister has a greater potential for interference between experiments.

Another significant accomplishment was our success in redirecting our efforts to emphasize issues of environment, safety, and health in response to the Secretary of Energy's call for full compliance by all Department of Energy facilities. During FY 1989, the NTES Program has been proactive in the self-assessment of our operations and has made considerable progress toward achieving a "full compliance" attitude and a standard of excellence. We will increase our efforts toward this commitment to quality in all aspects of our work in the coming year.

A singular and laudable success that we want to emphasize was the NTES participation in supporting the U.S.-Soviet negotiations at Geneva, Switzerland, toward a Threshold Test Ban Treaty (TTBT). NTES personnel devoted considerable effort and played a significant role in defining the technical and operational specifics of the treaty's protocol, including specifying geometry limitations for the CORRTEX yield verification measurement and defining operational and procedural details to ensure that the testing party can function appropriately within the limits of the treaty. The TTBT will most likely be ratified in the near future, and in FY 1990, we will focus on implementing the provisions of a TTBT at the NTS and in the U.S.S.R.

This is our second annual report on the progress of the NTES Program. As in our previous report, we have chosen an unclassified format to broaden the exposure of our research and development activities. Of course, a considerable amount of our work is classified and must be reported in a manner that limits distribution to the weapons community. However, we strive to maximize the amount of work we can report in the open literature.

This report includes articles from the four groups of the NTES Program: Prompt Diagnostics, Field Operations, Nuclear Chemistry, and Containment. (The FY 1988 *Annual Report* describes the NTES organization and the responsibilities and functions of each program element.) We include here all work funded by LLNL's Weapons Program, including Weapons Supporting Research.

World and national politics continue to evolve at an astounding pace. Their impact on the policies and practices of nuclear deterrence and the requirements for environmental sensitivity will profoundly influence our Laboratory. Pressures to further constrain nuclear testing will increase as will, ironically, the requirements for additional testing. In either event, the result will be still greater demands for more data from each nuclear test. Clearly, the goals of the NTES—enhanced science, enhanced efficiency, and enhanced quality—must remain the same. The policy of the NTES is to identify and cultivate those technologies and capabilities in which we are unique, to hone our abilities to maximum efficiency, and to remain flexible to respond to the changing directions of the future by applying our talents to the good of the Laboratory and the nation.

Prompt Diagnostics

1

The role of the experimentalist in the Prompt Diagnostics Program is to provide data with which to confirm developing theories in weapons physics and to ensure that descriptions of those physical processes are included properly in the codes used for designing nuclear explosives and other weapons concepts. Our laboratories include conventional, although unique, aboveground facilities in Livermore and elsewhere in the United States and underground experiment capabilities at the Nevada Test Site (NTS). In this *Annual Report*, we will cover experiments performed both above and below ground.

We also discuss theoretical modeling of our experimental observations. The scientific method requires close ties between experimentalists and modelers to guide each other in experiment design and confirmation of theories. Thus, in

FY 1989, we expanded our ability to model the phenomena being measured. This capability was especially fruitful in keeping fast-turnaround laboratory experiments well focused.

In all of our activities, we chose the direction for our work through close collaboration with nuclear design physicists, highlighting those areas of uncertainty in physical processes important for weapons operation. The underground and laboratory experiment programs, as well as the experiment development effort necessary to address tomorrow's issues, are motivated by the need to push toward first-principles understanding of each of these processes.

In FY 1989, we demonstrated outstanding advances in downhole experimental physics, particularly in areas of x-ray spectroscopy and high-bandwidth measurements. The applications and data obtained from these technologies are

classified, so they cannot be published here, but we discuss the technologies in several articles.

The general thrust of the experimental program in the laboratory is to simulate, on a microscopic scale, the phenomena observed in a weapon on the macroscopic scale. Thus, for example, we observed microgram quantities of materials heated to weapons-like conditions and performed other simulations scaled in a manner that enabled us to translate the physics observed to weapons regimes.

In FY 1989, we developed or demonstrated several advanced experiment technologies for underground experiments. These technologies generally fall into two classes: techniques for returning ever-increasing quantities of high-quality data from experiments, mainly using streak cameras and their supporting hardware and software; and other electro-optic technologies for making high-fidelity, high-bandwidth (multigigahertz) measurements. Again, the motivation for this development is the

requirement for higher-resolution data—better temporal, spatial, and spectral resolution. This data explosion is needed to challenge the physics models in increasingly sophisticated weapons design codes.

Finally, we look to the future with a few papers describing areas in which significant progress is expected in FY 1990. Most notable are experiments that will help us evaluate the applicability of laboratory measurements to weapons physics issues.

Experimental Physics

High-Energy Gamma Rays as a Fusion Diagnostic

K. E. Sale

We are beginning to work on new methods to measure the time history of fusion-burn events involving high-energy gamma rays. For our experiments, we define "high energy" as ranging from 10 to 25 MeV. By using gamma-ray-based techniques to diagnose hot deuterium-tritium (DT) plasma, we can achieve very-high-fidelity measurements. In fast-burning plasmas, energy dispersion distorts neutron data by obscuring the time history of the burn at a distant detector. The obscuring occurs because higher-energy neutrons travel faster and arrive at the detector earlier than lower-energy neutrons. However, all photons travel at the same speed, so the time history of a fusion-burn event is preserved in the gamma-ray signal.

In a burning DT plasma, the main fusion reaction is $d(t,n)\alpha$, which produces 14-MeV neutrons. A rare radiative-capture fusion branch produces a 16.7-MeV gamma ray, $d(t,\gamma)^5\text{He}$, which has been investigated for use as a diagnostic at the Nevada Test Site (NTS). The diagnostic use of the gamma rays from this branch is the subject of the article in this volume by M. Garcia on the high-current gamma monochromator.¹ The radiative capture reactions are also being investigated in laboratory experiments at the California Institute of Technology, Pasadena (Cal Tech).²

During the Cal Tech experiments, researchers saw a large, unanticipated background of high-energy gamma rays and concluded that the gamma rays were created when fast neutrons from the main fusion reaction were captured in the target and detector

materials. After observing the neutron-capture gamma rays, LLNL researchers realized that they could be used as a fusion diagnostic if some mass of nearly any target material was near the burning DT mixture. These secondary photons are of interest because the cross section for the $d(t,\gamma)$ reaction is extremely small compared with the cross section for the neutron branch. (The ratio of cross sections is about 1×10^{-5} .)

To use gamma rays as a fusion diagnostic, we must be able to calculate the production rate of neutron-capture gamma rays and are, therefore, starting a program to make laboratory measurements to support such a calculation. We will measure the number of gamma rays emitted with a given energy and at a given angle, with respect to the incoming neutron velocity per incident neutron for a range of incident neutron energies. The measured quantity, the differential cross section, is denoted as:

$$\frac{d\sigma}{dE_n dE_\gamma d\Omega_\gamma} \quad (1)$$

where σ is the cross section, E_n and E_γ are the energies of the incoming neutron and outgoing photon, respectively, and $d\Omega_\gamma$ is the gamma-ray solid angle. We will measure these reactions on various targets such as lead, iron, and actinide nuclei and are constructing a new beamline and detector system for this purpose at the LLNL tandem Van de Graaff facility.³ We will then use the pulsed-beam facility of the tandem to make 2- to 15-MeV deuteron beams, which we will direct into a gas cell filled with deuterium gas. Neutrons from the

$d(d,n)^3\text{He}$ reaction will exit from the gas cell to strike the target containing the material under investigation. By changing the energy of the incoming deuteron beam, we can vary the energy of the neutron beam.

A large NaI-crystal spectrometer system will detect the gamma rays produced in the target. The central detector of this system is a 10-in.-diam $\times$ 12-in.-long cylindrical NaI crystal. The quoted energy resolution of this detector is 3% for 6.13-MeV photons. A second detector consisting of a 4-in.-thick annulus of plastic scintillator surrounds the NaI detector and will be used as an anticoincidence detector. The second detector will perform two important functions. First, it will detect events in which all of the energy of a gamma-ray shower that starts in the NaI crystal is not fully contained in the crystal. We must eliminate these events to obtain clean gamma-ray spectra. Second, it will detect events caused by cosmic rays passing through the detector, which also must be rejected.

Because the cross sections we will measure are quite small, we must also eliminate background events. Therefore, we want to shield against unwanted particles entering the detector and remove background signals. To eliminate the unwanted particles, we will surround the detector with several layers of passive shielding. The innermost layer will be lead, which offers excellent protection against background gamma rays but is relatively poor at stopping neutrons. In fact, neutrons that do stop in the lead will also produce unwanted gamma rays.

Therefore, to keep these neutrons out of the lead layer as completely as possible, we will construct the next layer of B_4C -loaded epoxy resin. Boron absorbs slow neutrons with a very high probability and, thus, will greatly reduce neutron flux into the lead layer. The outermost layer of shielding will be boron-loaded polyethylene, its main purpose to slow the fast neutrons so the boron in this layer and the preceding one can absorb the neutrons before they enter the detector. These lead, B_4C , and polyethylene layers constitute the passive shielding against background events.

The background signals will be eliminated by using time-of-flight techniques. Because the distances between all components of the experiments remain fixed, all events of interest will occur at some fixed time relative to the arrival of a pulse of deuterons at the gas cell. By looking only at events that come in a certain time window around that time, we can achieve a high degree of discrimination. To obtain high-quality energy spectra, we will reject events in which part of the gamma-ray energy escapes from the crystal by looking for coincidences between the NaI crystal and the surrounding plastic annulus detector. The timing and anticoincidence techniques constitute the active background rejection effort.

To measure the data we need, we will first select a deuteron-beam energy that yields the chosen neutron energy. Using this fixed neutron energy, we will measure the energy spectrum of the gamma radiation. By repeating this process at several angles for each incident neutron energy and by performing the entire set of measurements for each target material of interest, we can extract the information we need.

In parallel with the experimental efforts on neutron-capture gamma rays, we will pursue theoretical and phenomenological ways to understand the data so we can extend our results to isotopes other than those we investigate experimentally. Neutron radiative capture is usually viewed within the phenomenological framework of the direct/semidirect model.⁴ In this model, the transition is described as the (coherent) sum of the two terms. The direct term describes a situation in which the incoming neutron makes a radiative transition from its scattering state directly into a single particle state of the final nucleus. The semidirect term describes a situation in which the target nucleus is excited into a collective state when the neutron is captured into the same single particle state. The gamma ray then is emitted from the de-excitation of the compound nuclear state. This second, collective part of the transition is responsible

for the well-known giant dipole resonance in radiative capture reactions. Another model we are evaluating is based on calculating the pre-equilibrium relaxation processes in the excited compound nucleus.⁵ In this approach, measured photon-absorption cross sections are used in a hybrid model of pre-equilibrium decay.

In summary, we have begun to use high-energy gamma-ray diagnostics in experiments at the NTS and are starting the laboratory experiments required to make high-quality measurements of fusion burn in hot DT plasmas.

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High-Current Gamma Monochromator

M. Garcia

We designed a high-current gamma monochromator (HCGM) to measure the deuterium-tritium (DT) reaction rate in a nuclear primary device. Our technique is to monitor the fusion-gamma-ray time history using a Compton electron monochromator coupled to microchannel-plate photomultiplier (MCP-PM) tubes via a Cherenkov optical system. The challenge is to detect 16.7 ± 1 -MeV fusion-gamma-ray photons, with a pulse of about 1 ns full width at half maximum (FWHM), against a nearly simultaneous background of 2-MeV, fission gamma rays, which are about 10^5 times more numerous.

Also contributing to the high-energy gamma-ray flux are emissions resulting from the capture of fast neutrons from the fusion reactions of interest in nearby metal parts.¹ Unlike the fusion-gamma-ray photons emitted simultaneously with the fusion reaction and whose intensity should provide a faithful time representation of the fusion reaction rate, each capture-gamma ray is delayed in time from its fusion source by the time necessary for its fusion neutron at 14.1-MeV energy to travel from the fusion reaction site to the capture medium. Whereas in the ensemble each neutron will travel different distances, the time dependence of the capture-gamma-ray flux will be a "smeared" representation of the fusion reaction rate. Despite the lack of true time fidelity, with proper computer modeling, we anticipate that even capture-gamma-ray data can give insight into the fusion process. Data from the planned downhole experiment and improved capture-gamma-ray

cross-section data from the laboratory will aid in that modeling. To distinguish the capture-gamma-ray emissions from the fusion-gamma-ray emissions, we designed HCGM units that were energy selective and had adequate time resolution to differentiate between the two sources.

The goal of the HCGM design was to provide high sensitivity with a fast temporal response. High sensitivity was gained at the expense of energy resolution; the HCGM energy band of 2 MeV is 13% of the mean Compton electron energy of 15.5 MeV. The design was to develop a 15.5-MeV Compton electron current as large as possible, to transport it through energy-selective magnetic optics far from the line of sight to a well-shielded detector with sufficient bandwidth to distinguish the leading fusion-gamma-ray pulse from the lagging capture gamma rays.

Electron Optics

Figure 1 is a scaled drawing of the HCGM. A 30-cm-long lead collimator with a 1-cm-diam bore defines an object spot on a 5-mm-thick beryllium plate that acts as the Compton converter. A 1.27-cm-thick steel collimator defines a Compton electron spray of about 7.6 deg that expands to about 4 cm in diameter by the time it reaches the first dipole magnet. We anticipated a mean electron kinetic energy of 15.5 MeV with a spread of ± 1 MeV within this cone from the interaction of 16.7 ± 1 -MeV fusion gamma rays with the beryllium plate.^{1,2}

The dipole magnets of the HCGM have a mean field of 0.533 T

(5.33 kG) and a 4-cm gap. The electron optics of the HCGM were calculated by Harald Enge (Professor Emeritus, Massachusetts Institute of Technology, Cambridge), and the dual dipole magnet system was built to his specifications by Field Effects, Inc., of Acton, Massachusetts. Figure 1 shows the envelope of electron orbits at the midplane of the magnets when the total electron energy is 16 MeV. The momentum spread is negligible (0%). The envelope increases vertically (perpendicular to the pole faces) from 1 cm (-0.5 to 0.5 cm) at the object spot to 4 cm (-2 to 2 cm) at the magnet entrance, where it bends inward because of the $\mathbf{j} \times \mathbf{B}$ forces (where $\mathbf{j}$ is current density, and $\mathbf{B}$ is magnetic field) induced by the rotated fringing field. Thereafter, the envelope remains within the 4-cm gap until it exits the second magnet and converges down to the 1-cm-diam object spot. Enge calculated these optics for a momenta spread as large as $\pm 6\%$. We selected this mirror-image optical system because aberrations induced in the beta rays by the first magnetic lens are cancelled by the second dipole magnet, resulting in a nearly isochronous system. This cancellation ensures high bandwidth and an image that is similar to the object spot in size, roundness, and divergence (or convergence) of electron trajectories. In our application, we placed two HCGM units in tandem in our line of sight. In the second HCGM, we reduced the magnetic field so that the electron-energy band of the instrument is 13.5 ± 1 MeV. The second HCGM was to observe capture gamma rays

and possibly fusion gamma rays within the energy band 14.7 ± 1 MeV. The measurements of these high-energy gamma rays on the Hornitos Event will give us new information for creating computational models of primary-device performance.

Light Optics

After passing over the image plane of the second magnet, the 15.5-MeV electrons burrow into

a Lucite lens that focuses the Cherenkov light they emit onto MCP-PM tubes. We chose this system because of its speed and gain (10^2 to 10^4). We anticipated that the HCGM electron current would be less than 1 mA, too small for Faraday cups, whose gain is 1. The light optics were designed by M. Grazer of EG&G, Amador Valley Office, Pleasanton, California, and the lenses were machined on the

diamond-turning lathe at LLNL. With respect to the electron trajectory, the Cherenkov emission is at 45.2 deg. As electrons pass through the plastic, their trajectories are deflected by multiple scattering, which causes the initially parallel electron beam to expand with depth. A cross section of the lens design is shown in Fig. 1.

The total Cherenkov emission is reflected internally from conical sides, then projected in parallel by toroidal lenses, and finally focused down to the detector photocathode by a converging-conical internal reflector and an axicon refractor in front of the detector. We calculated three-dimensional ray traces for the axisymmetric lens system and accounted for the effects of the detector entrance window and the position of the photocathode.

We made a bench test of the actual lens system at EG&G and determined that the net light transmission along the Cherenkov path length at 400 nm was 3%. This light was observed by an ITT 4126, single MCP-PM tube in an EG&G Las Vegas-designed, 50- Ω mount. The output of this detector was coupled to the Very-High-Bandwidth (VHB) Experiment at LLNL³ for high-fidelity transmission along optical-fiber cables to the recording station.

We coupled a second, low-bandwidth channel to the optical system to monitor the background suppression of the HCGM and embedded a 2.5-cm-diam by 5-cm-long Suprasil (quartz-like) rod in the forward Lucite lens at a depth of 24.5 mm. This rod has an MCP-PM mounted on its back end, where the detector fits within the inner radius of the toroidal lens. The Lucite-suprasil boundary is painted black, and the rod has a reflecting coating except on its end face near the detector. Thus, the first 28% of

Figure 1. HCGM scale drawing with dual dipole magnets. These units detected fusion-gamma-ray photons from a nearly simultaneous background of reaction-history nn' gamma rays and a massive background of fission-gamma-ray emission with an accuracy of less than 0.5 ns.

the electron range is in Lucite and accessed by a very high-bandwidth channel. The remaining 72% of the electron energy spreads in the Suprasil, where its light is collected into the low-bandwidth channel.

HCGM Bandwidth

The two HCGM units have 4×4 -cm electron apertures between the dipole magnets and exhibit a net impulse response out of the detector jumper cables of $\Delta t = 463$ ps, FWHM, or equivalently a -3-dB bandwidth of 671 MHz. We extensively tested these systems on the EG&G (Santa Barbara Office, California) linear electron accelerator (linac) and accurately duplicated Enge's calculations for the magnet-system impulse response and the energy dispersion at the aperture mirror plane.

HCGM Gain

The gain of the fast (to VHB) and slow (to cable) detector channels was directly measured on the linac.

The 50-ps, 15.5-MeV electron-beam pulses were shot through a 1-cm-diam collimator into an assembled, Lucite-suprasil lens-detector system at various current levels. The fast-channel gain is 1.22×10^4 , whereas the slow-channel gain is 1.29×10^4 . For very short pulses, the gain drops when the detector output exceeds 1 nC, the saturation limit.

HCGM Summary

On the basis of our experiments, we expected 0.004 electrons to pass through the HCGM magnets and into the Lucite and to deliver 50 electrons with an impulse response of 463 ps from the detector for each incident high-energy gamma ray.

During the Hornitos Event, both HCGM units successfully detected high-energy gamma rays. Although we are still analyzing these data, the essential conclusions can be stated. The measured ratio of fusion gamma rays to capture gamma rays to fission gamma rays was 1:10:1,000,000. The pulse shapes,

with respect to time of combined fusion-gamma-ray and capture-gamma-ray signals, in the range of 14 to 17 MeV were recorded with an accuracy of less than 0.5 ns. These pulses were clearly distinguished by the HCGM units despite the massive background of fission-gamma-ray emission. The systems had a temporal fidelity of 0.46 ns for the optical-fiber channel and 0.64 ns for the cable channel.

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The CRACKER Experiment on the Mighty Oak Event

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The understanding and control of neutron transport is critical in many areas of weapons physics, from nuclear-device design to experimental shielding. In FY 1985, improvements in codes used to calculate neutron transport led to proposals for more complicated

experiments and third-generation weapons. We designed the CRACKER experiment on the Mighty Oak Event to test these expanded calculational abilities before beginning an extensive experimental program. However, as a result of a containment

problem on the event, we were unable to retrieve our data until late FY 1988 or to analyze and compare it with our preshot calculations until FY 1989.

Our goal in FY 1985 was to capture and thermalize the prompt neutron flux from a nuclear device. To

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achieve this, we planned to place a 102- × 122- × 153-cm graphite box, encasing experimental detectors, in the main tunnel behind the Mighty Oak vacuum line of sight (LOS), as shown in Fig. 1. A 30- × 30- × 91-cm opening in the box faced the nuclear device. The detectors within the box were designed to measure the time history of the neutron flux. Because the time scales of this experiment

were longer than measurements normally made by L Division and the flux levels were lower, we needed to invent three detector systems to span the range of sensitivity we hoped to measure.

Detectors

Two detectors were variants on the fission-chamber concept. Their active element was ^{235}U , which

was required to detect the thermal neutrons. Both detectors (Fig. 2) consisted of 77-cm-long stainless-steel tubes. The first detector had interior walls coated with ^{235}U and used xenon gas as a scintillator. Fission fragments recoiling from the uranium coating would cause the xenon gas to fluoresce at 170 nm, a difficult wavelength to detect. These ultraviolet photons would then pass through a MgF window into a photodiode detector with a CsTe photocathode. The current signal would be sent to the recording station via coaxial cables and recorded on oscilloscopes.

The second detector had only the bottom 30 cm of its tube coated with uranium and used a plastic scintillator. If the scintillator was excited by recoil fission fragments, it would emit visible light. Some light would reflect up the tube into a conventional photodiode, and the signal would be amplified and recorded as voltage vs time. We planned to convert the data to neutrons vs time after the event, using laboratory calibrations.

Both of these detectors and a background detector, which used ^{238}U and had no thermal neutron sensitivity, were calibrated at the National Institute of Standards and Technology reactor in Gaithersburg, Maryland. After carrying out the calibrations, we stored the detectors for 2 d to reduce their activation level below 1 mrad/h and then shipped them to the Nevada Test Site, where they were installed in the graphite box.

We developed a third detector, known as "der Spinner," in collaboration with the Westinghouse Hanford Laboratory at Hanford, Washington (Fig. 3). We used four plastic track detectors wrapped

Figure 1. Experimental arrangement of the CRACKER experiment on the Mighty Oak Event. The graphite box was placed behind the vacuum exposure tank. The working point was to the left. The CRACKER box was designed to capture and thermalize the neutron output from the nuclear device.

around an 8-cm aluminum cylinder, spinning at 60 Hz. This material "viewed" a sample of ^{235}U through a slit system. When neutrons generated fissions in the sample, recoil fission fragments would pass through the slit system and interact with the track-detector material, causing microscopic damage to the molecular structure. Thus, if we measured the number of tracks vs position on the track detector after the event, we could determine the time history of the captured neutron flux.

We planned to recover the detectors after the Mighty Oak Event and etch them in HF acid, turning each interaction point into a macroscopically observable track to be counted under a microscope. Figure 4 shows examples of tracks made before the shot with a laboratory ^{252}Cf spontaneous-fission source at different static exposure levels. We also used the source to measure the umbra/penumbral of the slit system. The measurements agreed well with calculations based on the geometry of the slit system (Fig. 5) and were valuable in analyzing the final data.

We made dynamic calibrations of the slit system using the LLNL Rotating Target Neutron Source-I as a pulsed source of 14-MeV neutrons. We triggered the accelerator to pulse once for each rotation of the cylinder. The measurements confirmed that the time resolution of the slit system was exactly what would be calculated from a convolution of the cylinder rotation speed and the slit width. We also confirmed that the system impulse response was broadened in a calculable way from the distribution measured in the static tests.¹

For the actual experiment, we used four track detectors: two strips of specially chosen mica² and two of MAKROFOL, a commercial

Figure 2. Design of the ^{235}U fission-chamber detectors. In the first detector, the interior wall of the metal tube is coated with ^{235}U and filled with xenon gas, which scintillates in the ultraviolet (UV). In the second detector, only the lowest 30 cm are coated with uranium, and the xenon is replaced with a plastic scintillator, which generates visible light.

Figure 3. Schematic of "der Spinner" detector. The rotor is driven by a synchronous motor and, using tunnel power, rotated at 60 ± 1 Hz. By measuring the number of tracks vs position on the track detector, we determined the time history of neutron flux.

plastic compound. We used a 20- and a 50- μm slit width for each material. The 20- μm slit was combined with a thick uranium deposit to give the best time resolution, and the 50- μm slit was chosen to increase the input signal if the flux fell below predicted levels.

Experiment

The CRACKER experiment on the Mighty Oak Event took place in April 1986. Within minutes of zero time, the innermost containment ring was breached. Although no radiation escaped the tunnel, the event area filled with radioactive

gases, and all oscilloscope data were destroyed. After a few months, preliminary tunneling indicated that radiation levels were still too high for human occupation or for recovery of the experimental data.

By late FY 1988, however, radiation levels subsided, and the Defense Nuclear Agency entered the area, took photographs, and retrieved the Spinner. The photos showed that the other two detectors and the background detector were destroyed. The only possibility of recovering data was if tunnel temperatures had remained low enough to keep the nuclear track detectors from annealing the damage caused by the fission fragments and losing all information. We shipped the Spinner to Hanford's facility for handling radioactive equipment and began analysis in FY 1989.

Results

All four track detectors survived and were carefully removed from the Spinner and etched in HF. In the removal process, one mica detector broke into two pieces, causing some ambiguity in the time history. However, when we viewed the

Figure 4. Photomicrographs of several track detectors exposed at the indicated flux levels with a ^{252}Cf source during static spinner tests. The detectors have been etched for 2 h in 49% HF acid. Flux level is at (a) 1.2×10^5 tracks/ cm^2 at 200 magnification; (b) 9.1×10^5 tracks/ cm^2 at 200 magnification; (c) about 1.2×10^6 tracks/ cm^2 at 200 magnification; (d) about 1.2×10^6 tracks/ cm^2 at 400 magnification; and (e) about 2×10^6 tracks/ cm^2 at 400 magnification.

Figure 5. Comparison of the calculated and observed slit transmissions obtained using the ^{252}Cf source. An important criterion for analyzing the shot data was that the experimental results have the same spatial distribution across the detectors as we measured in these tests.

detectors under a microscope, we found that the data on the mica detectors were still intact, but the data on the MAKROFOL detectors were destroyed. Because annealing temperatures differ for mica and MAKROFOL, we were able to establish the temperature bracket to which the Spinner was exposed.

We scanned the two mica detectors under a microscope and converted the number of tracks into digital data. Corrections for target thickness, linear velocity, slit-system solid angle, and time resolution were applied to the scanned data, converting the number of tracks per centimeter into fissions per microgram per second in the target, a number that was easy to compare with our calculations.

The final data from the experiment were of high quality, with a reasonable consistency between the two mica strips. The results agreed well in overall shape and magnitude with our preshot calculations.

By improving the calculational fits to these final data, we can test our transport codes in regions characterized by low neutron energy and multiple neutron collision, where we have had little previous experience.

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Measuring Electron Temperature in Nuclear-Driven Plasmas

P. T. Springer

Plasma-electron temperature affects atomic ionization and recombination processes, plasma ionization state, opacity, and spectral emission. It also determines the hydrodynamic motion of hot plasma. Knowledge of plasma-electron temperatures is essential to model the dynamics of nuclear-driven plasmas. These models are complex. Before complete thermal equilibrium can be established between radiation and matter, the driving spectrum and the

interactions of ions with x rays and electrons, as well as the generation and transport of x rays within the plasma, must be understood in detail. To test our knowledge of these processes, we measured the electron temperature of nuclear-driven plasma containing mid- and high-Z ions using the free-bound x-ray emission of highly stripped ions and compared them with theoretical predictions based on atomic-rate modeling. An accurate determination of the electron

temperature can be used to test models of interactions between nuclear radiation and ions in hot, dense plasmas, to precisely model atomic rates, and to design plasma systems that are pressure-matched for hydrodynamic stability.

To dynamically heat three plasma samples containing mid- and high-Z ions, we used x rays from a nuclear device. We experimentally determined the electron temperature vs time of each sample from the x-ray spectrum that resulted from

electrons recombining into the highly stripped ions. We used a fourth, low-Z sample to determine the source-scattered background and measured the spectra using a high-resolution-imaging bent-crystal spectrometer with subnanosecond time response. The plasma ionization states and temperatures for the differing atomic systems were inferred from their spectral intensities and shapes, respectively.

Review of Radiative Recombination

To measure the electron temperature, we chose a plasma process that would provide a signature of the electron temperature with x-ray spectroscopic diagnostics despite the nonequilibrium condition of the plasma. We investigated three methods to determine the temperature with x-ray spectroscopy using: (1) widths of x-ray transitions to infer the ion temperature from Doppler broadening, (2) ratios of

dielectronic satellite lines, and (3) the free-bound continuum emission shape. An examination of the free-bound continuum emission shape from the radiative recombination of electrons into highly stripped ions was the only method that yielded unambiguous measurements of the electron temperature.

In radiative recombination, a free electron makes a transition into a bound level of an ion, emitting an x ray. The energy of the x ray emitted is equal to the sum of the electron kinetic energy and the bound-state energy, as shown for a hydrogen-like ion in Fig. 1. Thus, in the process of the electron's recombination into a given bound level, a unique relationship is established between the initial energy of the recombining electron and the energy of the emitted x ray. Therefore, the x-ray spectral distribution is not only related to the electron-energy distribution or temperature but also depends on an atomic-recombination

cross section, which can be calculated numerically using fully relativistic Dirac-Hartree-Fock wave functions. Because the electron-collision time is fast, the electron-energy distribution should be Maxwellian. Therefore, aside from a normalizing constant, the distribution J_e of electrons with energy E_e should be given by:

$$J_e \propto N_e \exp(-E_e/T) E_e dE, \quad (1)$$

where N_e is the electron density and T is the electron temperature. The exponential falloff in the electron-energy distribution reflects itself in an exponential falloff in the recombination x-ray spectrum. Aside from a normalizing constant, the x-ray emission rate $\epsilon_H(E)$ caused by recombination with bare ions that produce the hydrogen-like free-bound continuum is given by:

$$\epsilon_H(E) \propto N_e N_{\text{bare}} \exp[-(E - I)/T] \times \sigma_{\text{ph}} E^3 dE, \quad (2)$$

Figure 1. (a) An energy-level diagram of a hydrogen-like ion showing the bound levels represented by $n = 1$, $n = 2$, and $n = 3$, where n is a principal quantum number of the ionic state. The diagram also shows the continuum of free states having an occupation described by a Maxwellian distribution of electron energy [$\exp(-E_e/T)E_e$]. The bound-bound transitions, 2-1 and 3-1, are indicated as well as a free-bound x-ray transition, which lies in energy above all bound-bound-transitions. (b) The x-ray emission spectrum from bound-bound and free-bound transitions into both the $n = 1$ and $n = 2$ levels. The Maxwellian energy distribution implies an exponential falloff in the spectral emission. The rate of falloff is determined by the electron temperature.

where E is the x-ray energy, N_e is the electron density, N_{bare} is the density of bare ions, I is the ionization potential, and σ_{ph} is the photoelectric cross section. For an optically thin plasma, when the energy variation of $\sigma_{\text{ph}} E^3$ is removed, the emission has a simple exponential falloff characteristic of the electron temperature. Although the intensity of the free-bound continuum emission depends on the plasma density, temperature, and ionization state, the spectral shape depends principally on the electron temperature.

The spectrum from radiative recombination into excited levels and into ions with an arbitrary degree of ionization will be a sum over all possible excited levels and all degrees of ionization. In the region of the continuum thresholds of a given shell, the emission spectrum is complex, containing free-bound emission from lower states of ionization and high Rydberg bound-bound transitions from higher states of ionization. Nevertheless, above the highest energy-continuum threshold, hydrogen-like for K-shell systems and lithium-like for L-shell systems, the recombination spectrum will again have a simple exponential falloff indicative of the electron temperature.

Modeling of Plasma Conditions and X-Ray Emissions

A dynamic model of the plasma conditions is created employing an atomic-rate-solver code, which uses detailed atomic models for the ions in their various possible ionization states and accounts for known atomic processes and interactions with both x rays and electrons. Driven by a specified time- and frequency- (energy-) dependent

x-ray intensity, the code determines the plasma evolution, the plasma temperature, the nonlocal thermodynamic equilibrium (non-LTE) level populations, intralevel transition rates, and the generation and transport of radiation within the plasma. We calculate the temperature from the known plasma heating and cooling mechanisms: Auger decay, photoionization, electron-collisional excitation and ionization, bremsstrahlung, and their inverse processes.

We use a postprocessor code to calculate the spectral emission that escapes the plasma using the predictions of the level populations vs time. The code determines the bound-bound and free-bound sample emissivities. We include the plasma optical depth of both bound-bound and free-bound transitions to calculate the emission that escapes the samples.

For the electron-temperature experiment, we chose the mid- and high-Z ions as complementary K- and L-shell systems. The K-shell ionization potential of the mid-Z ion lies slightly above the highest-energy (lithium-like) L-shell continuum threshold of the high-Z ion. Thus, the free-bound spectral regions are similar, and the elements can be mixed with no spectral interference but a vastly superior signal-to-noise ratio. The K-shell spectra are easier to interpret than the L-shell and can determine the electron-energy distribution without the assumption that it is Maxwellian. With the calculated source intensity, the mid-Z sample is predicted to strip well into its K-shell, with its peak ionization hydrogen-like. With the calculated source intensity, the high-Z sample is predicted to strip well into its L-shell, with the peak ionization

nitrogen-like. The samples are predicted to be hydrodynamically stable during the experiment.

Electron-Temperature Experiment

Measuring the electron temperature was a diagnostic challenge requiring the development of a high-precision, multiobject x-ray spectrometer. Previously, spectrometers were not used downhole to image separate samples because of the stringent pointing accuracy required. We determined the x-ray flight path using an optical laser to simulate a point source on the mid- and high-Z samples and a downhole active-alignment system to remotely adjust the spectrometer positioning, with the laser focus recorded by a linear Reticon as a reference. Although we examined only four plasma sources, this arrangement gave us a spectrometer pointing accuracy of 20 μrad that exceeded the 100- μrad spectrometer resolving power. This pointing accuracy would have allowed us to resolve more than 20 separate plasma sources simultaneously, greatly enhancing our capability to increase the data-return rate.

A schematic of the experimental setup is shown in Fig. 2. Four samples are heated by nuclear radiation from the source. The free-bound continuum spectrum is measured in all samples simultaneously using a single spectrometer. A curved crystal spectrometer with redundant x-ray detection systems provides both spatial and spectral imaging of the four samples with subnanosecond resolution. The spectrometer energy resolution is set at about 30 eV by the defining slit. Both CdS-phosphor and GaAs-photoconductive detectors were used to measure the crystal-dispersed x-ray intensity. The spatial

Figure 2. Setup for the electron temperature experiment. The curved crystal spectrometer is designed to include spatial and spectral imaging of four samples, redundant x-ray detection systems, downhole timing to the x-ray drive, and active alignment.

resolving power is approximately 100- μ rad, full width at half maximum, giving an insignificant level of crosstalk.

To align the spectrometer to the samples so the Bragg-reflected x rays strike at the position of the fiber arrays, we use an active alignment system. We time the experiment downhole to the x-ray drive using a source x-ray-driven phosphor-light marker and employ a suite of filter-fluorescence experiments to characterize the source intensity and spectrum vs time.

A thin, optically flat quartz 502 crystal is attached to a copper-plated Pyrex substrate, which is diamond turned with optical tolerances to a specified radius. Using copper on the substrate reduces the x-ray-scattered background from the crystal by a factor of 5. X rays from the different samples pass through a vanadium filter; are Bragg-reflected; pass through a narrow, fused-silica vacuum window; and are focused over an extended region on the detector plane. The x rays deposit their energy in the subnanosecond phosphor, indium-doped CdS. A discrete quartz-fiber array transmits the light to two optical streak cameras. The streak cameras provide a dynamic range of about 500, which we need to record the large signal variations in both x-ray spectrum and time, with an allowance for calculational uncertainties.

Because we inferred the temperature from a measurement of the spectral shape, we had to characterize the spectrometer sensitivity with extreme accuracy across the entire spectral range. We accomplished this by using continuum sources and photon-counting techniques and performed the spectrometer calibration using both line emission and

continuum bremsstrahlung from laboratory x-ray tubes. We used pulsed and dc x-ray sources to determine the phosphor efficiency vs energy and incident angle and pulsed Lambertian light sources of the correct color to determine the fiber's transmissions and streak-camera efficiency. When we combined these results, we obtained a spectrometer characterization that had a relative accuracy of about 5% over the spectral region covered.

Data Reduction and Results

Figure 3 shows the streak-camera record obtained from a nuclear event, giving the spectral emission from each sample vs time. For each time element recorded in the streak camera, we extract the intensity in each fiber and obtain its intensity profile from calibration data. We then construct a model in which the position and intensity in each fiber is allowed to vary independently. We compare the model with the observed data and optimize it on the basis of χ^2 . Figure 4 shows an example of a single row of streak-camera data and the best-fit model for that row. We apply similar fits

to streak-camera calibration data to relate the observed signals to the incident phosphor-light intensity vs time. We then use the spectrometer calibration to relate the observed phosphor-light intensity to the plasma spectral emission vs time. We extract data from 40 separate rows of the streak camera, resulting in 2400 independent data points per streak camera.

We use the spectral shape of the observed plasma emission to infer the temperature vs time for each sample. To determine the bomb-scattered intensity from each sample, we modeled their relative scattering efficiencies using the atomic-rate-solver code and included scattering from both bound and free electrons in the calculation. The measured spectrum from the background sample is dominated by source-scattered radiation and is a measurement of the source spectrum vs time. Thus, the measured spectrum from the background sample can be directly normalized by the relative scattering efficiency vs energy to obtain the background spectrum for each of the other samples. The dominant

Figure 3. Raw data from the electron temperature experiment as returned on the streak-camera image. The streaked image is analyzed to determine the x-ray emission vs time in the four separate samples.

uncertainties in the background intensity will then stem from the plasma opacity corrections.

We can fit the shape of the background-subtracted spectra to determine the electron temperature, with slight corrections for the plasma optical depth and gradients in the plasma. In the data presented here, we assume that the plasma emission is uniform over the plasma volume and that the emission has the functional form:

$$\text{Spectrum} = AE^3 \{1 - \exp[-od(E)]\} \times \exp[-(E - I)/T], \quad (3)$$

where A is a normalizing constant, and $od(E)$ is the optical depth vs energy of the plasma. We determined the plasma opacity from the model predictions and derived the

temperature by best fit to the observed data. We normalized the error bars that we derived from the fit to give a χ^2 per degree of freedom of unity. Thus, the errors reflect not only the true statistical uncertainties in the data but also the quality of the fits to the data. Figure 5 shows the results of a fit to the mid-Z spectrum at the peak of the x-ray drive. The exponential falloff of the data verifies that the electron distribution is Maxwellian. The precision in the temperature derived in the fit is about 3%. Figure 6 shows the derived temperature for the mid-Z sample and a comparison with a model calculation.

Knowledge of the plasma opacity is not critical for the data interpretation because changes in the plasma opacity would give spectral modifi-

cations that tend to cancel one another. Corrections for the escape probability of the emitted x rays reduce the inferred temperature with increasing opacity. Conversely, corrections for source-scattered backgrounds increase the inferred temperature with increasing opacity. These two effects tend to cancel each other so the plasma-opacity effects, which in isolation represent a 10% correction, are only a few percent. In the presence of gradients in the plasma emission and temperature, the temperature derived is altered from that obtained using an isothermal, volumetric model. Thus, the effective plasma emission is closer to the heated surface. This tends to raise the temperature inferred from both the data and the model. The opacity and gradient corrections are also included by using the codes to predict the falloff of the emitted spectrum.

Figure 4. Raw data from a single row of the streak-camera image, displayed as dots. A model describing the individual fiber profiles, displayed as a solid line, is constructed from a best fit of individual fiber profiles to the observed data. The x-ray intensity into each fiber is determined from this model.

Figure 5. The measured spectrum from the mid-Z sample and the best-fit model. The background indicated is measured using the low-Z sample. As expected, the spectrum falls approximately exponentially with x-ray energy, indicating a Maxwellian electron-energy distribution. We use this rate of falloff to determine the electron temperature. The temperature accuracy from the fit is 3%.

Conclusions

We measured the temperature of both K- and L-shell nuclear-driven plasmas using the free-bound continuum radiation of the highly stripped ions. The quality of the measured spectra was high, allowing accurate comparisons between data and model predictions. The accuracy of the derived temperatures for the K-shell radiators was between 3 and 5%. This accuracy critically tests the models of the interactions between nuclear radiation and ions in hot, dense plasmas and enables us to precisely model atomic rates and to design plasma systems that are pressure-matched for hydrodynamic stability.

Figure 6. For the mid-Z sample, this graph shows a comparison between the measured temperature and ab initio calculations using atomic-rate modeling.

X-Ray Laser Kinetics Experiments on the Nova Laser

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In 1984, an experimental team produced the first unambiguous demonstration of an extreme ultraviolet (XUV) amplifier at LLNL's Novette laser.¹ A lengthy series of investigations conducted from 1985 to 1987 on the two-beam facility at the Nova laser uncovered some questions relating to our basic understanding of the mechanisms governing charge-state distributions, excited-state populations (which create the inversions necessary for stimulated emission), and photon trajectories.² In FY 1989, following an extensive shutdown of the two-beam facility, we began a detailed experimental investigation of these so-called "kinetics" issues.

Although a variety of methods have been proposed for producing XUV and soft x-ray amplifiers, and a number of these are being experimentally investigated by various groups around the world,³ our interest is in understanding the physical mechanisms at work in an XUV amplifier setup involving neon-like ions.

Neon-Like Extreme Ultraviolet Amplifiers

A neon-like ion is an atom with enough electrons removed so that only 10 remain bound to the nucleus (as in neutral neon, hence the terminology). Because this electronic configuration represents a closed-shell

structure, the neon-like species is especially stable and is present to a significant extent in plasmas of medium atomic number ($Z \sim 25-50$) over a large range of temperatures. In addition, the atomic physics of excited neon-like ions lends itself to the buildup of population inversions. The first (i.e., lowest-lying) excited state has the electron configuration $2p^5 3s$, which is strongly radiatively coupled to the $2p^6$ ground state. Population in the $2p^5 3s$ state radiatively decays to the ground state in a characteristic time of about 10^{-13} s. The next higher-energy excited state has configuration $2p^5 3p$ and is forbidden by angular momentum selection rules

from decaying directly by dipole radiation to the ground state. Higher-order mechanisms take place in a characteristic time of about 10^{-10} s. Hence, a randomly distributed ensemble of excited neon-like ions very quickly develops an inversion between the 3p and 3s levels and radiates amplified spontaneous emission (ASE) on different transitions ranging in energy from about 30 to over 120 eV, depending on atomic number.

In our FY 1989 study, we concentrated our effort on two elements, germanium ($Z = 32$) and silver ($Z = 47$). The specific energy levels of relevance to the XUV amplification in these elements are shown in Fig. 1. Our past experiments with neon-like selenium unambiguously identified five lines that undergo ASE in these systems;⁴ the number of states (hence, the number of lines) involved arises from fine-structure splitting in both the upper and

lower laser levels produced by interactions between the angular momenta of the core and the excited electron. The transitions are conveniently labeled by the total angular momentum, J , of the upper laser level as shown. Experimentally, what has been seen in the XUV for all elements tested to date is a dominance, in both gain and absolute intensity, of the two $3p_{3/2} J = 2$ lines as shown in Fig. 1, followed by the long-wavelength $J = 2$ and the $J = 1$. The weakest is usually the $J = 0$. Table 1 summarizes gains observed at LLNL for the five lines in germanium, selenium, yttrium, molybdenum, and silver.

These observations are to some extent at variance with our understanding of the populating mechanisms in these systems. Originally, it was believed that the dominant means of populating the upper laser levels was direct excitation from the ground state through electron-ion

collisions. Straightforward (but highly detailed) rate equation analysis of the collisionally modeled excitation kinetics predicted the highest gain on the $J = 0$ line, where the lowest gain is actually observed.⁵ Subsequent modeling efforts, which included the effects of dielectronic recombination, reduced the disparity somewhat, but any reasonable parameterization still puts the $J = 0$ gain at least comparable to that of the bright $J = 2$ lines.⁶

Outside researchers have offered two explanations as possible solutions for the " $J = 0$ problem." The first speculates that we are fundamentally mistaken about the dominant pumping mechanism in our amplifiers, that recombination cross sections are about an order of magnitude higher than we predict, and that recombination determines the bulk of the excitation in our systems.⁷ Because recombination naturally favors higher angular momentum states, the $J = 2$ states automatically come out with the highest gain and the $J = 0$ states come out with the lowest. The second solution suggests that the spectral linewidths of the amplified lines are narrowed below their Doppler width by an effect called "Dicke narrowing" and that, along with plasma turbulence, which gives large local differential Doppler shifts, they cause the effective macroscopic gain to be reduced because of frequency mismatch between adjacent turbulence cells.⁸ The Dicke narrowing is most pronounced for the $J = 0$ level, and, hence, its gain is most reduced.

From 1985 to 1987, experiments were done to test some aspects of these proposed explanations. An accurate, absolutely timed streak-camera recording of the $J = 2$ angular footprint vs time demonstrated that effectively all of the amplification

Figure 1. (top) Excited-state energy levels in neon-like germanium and silver involved in XUV amplification. (bottom) Schematic of relative line positions and axial spectrometer coverage (shaded rectangles). Note that, in silver, the weak $J = 0$ line shifts in position relative to the other lines, and the excited-state splittings are increased.

was occurring in the very early part of the driving laser pulse.⁹ By the time the Nova pulse had peaked, the XUV amplification had turned off. This is not the temporal signature expected to be characteristic of a recombinantly driven amplifier. In addition, the absence of significant fluorine-like gain in the XUV indicates a problem with the recombination-predominant explanation.¹⁰ We are presently developing the diagnostic capability to measure XUV lines with sub-Doppler resolution, which will yield line-shape information that can be used to test the Dicke narrowing hypothesis.

Some of our past observations point to the need for additional research to better understand some of the processes involved. In long selenium amplifiers, where the gain-length product exceeds 12, pronounced asymmetry is apparent in the angular footprint of the beam.⁹ The time-integrated XUV intensity pattern is double-lobed, with each lobe about 11 mrad wide and centered about 8 mrad above and below the plane of the target foil. There is an intensity minimum at the physical on-axis location. The targets are composed of a layer of laser deposited on a thin plastic substrate, producing a natural target asymmetry. This asymmetry carries over to the footprint pattern in that the lobe centered above the laser side of the target is about five times brighter than the lobe centered above the plastic side. Also, spatially resolved images of the selenium amplifier lines indicate a source region of less than 40 μm (Ref. 11), which is quite small compared with the few hundred micrometers predicted for an expanded plasma from a hydrodynamically thin foil target.⁵ These observations, coupled with the early time history indicated from the absolutely timed,

streaked measurements mentioned above, strongly indicate that the real neon-like XUV amplifier is predominantly a high-density, nonuniform medium, evolving in time to the low-density-gradient amplifier previously suggested.

Since the two-beam facility was shut down in 1987, several groups from around the world have succeeded in producing neon-like XUV amplifiers. A team from the Naval Research Laboratory demonstrated amplification from neon-like copper and germanium in 1987 (Ref. 12) and from neon-like zinc, arsenic, and selenium in 1988 (Ref. 13). Also in 1988, a British group produced and coarsely characterized a germanium amplifier.¹⁴ In 1989, a team from the University of Rochester, New York, developed neon-like germanium amplifiers.¹⁵ In all of these cases, the targets were hydrodynamically thick with single-sided irradiation at 1.06 μm . These observations were very similar: all gains were measured higher than those that we measured, and the $J = 0$ line gain stood out as being remarkably high, comparable to the $J = 2$ lines. The angular

footprints in these cases were also similar, with a single observed lobe at approximately 10 mrad above the target plane. Given that a thick target inherently develops and maintains a strong electron density gradient, refractive photon trajectories can produce such a footprint.

Neon-Like Experiments in 1989

In FY 1989, we were challenged to design and conduct experiments that would critically test our modeling. With a limited shot budget for that year (we had 27 shots in 5 d from late August into September), we concentrated for the most part on two specific lines of inquiry: the demonstration of XUV amplification in neon-like silver and the somewhat extensive characterization of neon-like germanium amplifiers under various ionization conditions. Silver has by far the highest atomic number ($Z = 47$) of any target material that we use for the production of a neon-like XUV amplifier; even the demonstration of lasing is an exercise in the extrapolation of hydrodynamics and atomic physics scaling

Table 1. LLNL-measured gains for neon-like XUV amplifiers.^a

	Gain (cm^{-1})				
	Germanium ^b $Z = 32$	Selenium ^c $Z = 34$	Yttrium ^c $Z = 37$	Molybdenum ^c $Z = 42$	Silver ^b $Z = 47$
$J = 0$	1.0 (19.64 nm)	2.4 (18.243 nm)	(15.50 nm)	0.0 (14.16 nm)	d
$J = 2$	2.6 (23.22 nm)	4.0 (20.638 nm)	4 (15.50 nm)	4.1 (13.10 nm)	6.6 (9.93 nm)
$J = 2$	2.8 (23.63 nm)	3.8 (20.978 nm)	4 (15.71 nm)	4.2 (13.27 nm)	4.3 (10.03 nm)
$J = 1$	2.3 (24.74 nm)	2.2 (22.028 nm)		2.9 (13.94 nm)	d
$J = 2$	1.8 (28.64 nm)	3.5 (26.294 nm)			d

^a These gains are derived from measured relative intensities by fitting to the so-called Linford function.⁸ Also measured by the LLNL group but at the Phebus laser at Limeil, France, were gains for the $J = 2$ strontium lines:⁹ 4.4 cm^{-1} (16.41 nm), 4.0 cm^{-1} (16.65 nm).

^b Measured in the 1989–90 campaign.

^c Measured in the 1985–86 campaign.

^d These lines have been observed in our on-axis XUV spectra for silver, but more data are needed to determine gains, if any.

relations. Importantly, the energy-level separation for silver is significantly larger than that for selenium, which results in shorter-wavelength XUV ASE radiation. However, more importantly, a number of $n = 3$ to $n = 2$ electric quadrupole transitions seen in the 3- to 4-keV region originate in the upper laser levels. Because of their multipolarity, the lines are optically thin and, hence, provide a direct measure of the excited-state population density.

Germanium, in contrast, has a lower atomic number ($Z = 32$) than selenium and is, therefore, slightly easier to ionize. The twofold increase in Nova beam energies that have been achieved since we conducted our first experiments in 1986 has given us a unique opportunity to study ionization kinetics and their effects in real amplifier-geometry targets. Specifically, we can achieve maximum irradiances in line focus geometry of about 10^{15} W/cm² in 1 cm of target length (with an obvious inverse relationship between target length and maximum target

irradiance); the nominal selenium irradiance is 6×10^{13} W/cm². Because the average electron energy scales approximately as the electric field strength of the Nova pulse (i.e., the square root of the intensity), we can achieve about a factor of 3 variation of the collisional excitation energy in either direction from nominal, provided we efficiently couple the pump laser energy into the plasma by appropriately varying target thickness.¹⁶ This allows us to substantially under- and overionize germanium amplifiers. The overionized case is of particular interest because, once the L-shell ionization energy is breached, a large variety of charge states can be produced. Some of these, such as fluorine-like ions, are predicted to show gain on certain 3p–3s transitions. Germanium is also of interest as a point of comparison with the work done elsewhere.

The practical emphasis through most of FY 1989 was to assemble and field an array of diagnostic instrumentation in the two-beam chamber in order to generate high-resolution

temporal- or, in some cases, angular- or spatial-resolving spectra in the XUV and x ray. The design of the array had to be flexible enough to accommodate the varying energy coverages required by the widely different experiments performed in the chamber. The diagnostics included:

- Two MCPICS, Rowland-grating XUV-survey spectrographs with time-gated microchannel-plate detectors, one located along the amplifier axis and the other located well off-axis. (MCPICS is a microchannel-plate-intensified grazing-incidence spectrograph.)
- A streaked, flat-field spectrograph (SFFS), which is a varied-line-space grating instrument coupled to an x-ray streak camera for detection of the XUV emission in the on-axis location opposite the on-axis MCPICS.
- Two streaked, crystal x-ray spectrographs (the Keanetech and XCSS).
- Eight time-integrated crystal x-ray spectrographs (the Henways).
- A time-integrated spatially imaging crystal x-ray spectrograph (the SIS).
- An x-ray pinhole camera.

Some of our first data came from the silver amplifiers. We were limited to target lengths of approximately 1 cm because of the high irradiances required to strip the 37 electrons. We observed bright, directional ASE emission on the major $J = 2$ lines at 9.93 and 10.03 nm from a 9-mm target shot at maximum irradiance. A cursory survey of the effects of varying target thickness indicated that the inversions were enhanced at greater areal densities. Using samples from the thickest targets prepared for the series ($150 \mu\text{g}/\text{cm}^2$), we initiated a brief length study to determine the gains. Axial XUV spectra from this survey are shown in Fig. 2. The relatively abrupt onset of the neon-like emissions with

Figure 2. XUV spectra from three silver amplifiers of different lengths. The extremely rapid rise of the amplified neon-like lines above background is indicative of a very high gain coefficient.

increasing length indicates high gain coefficients (Table 1).

The numbers should be interpreted with some caution, however, because of the poor statistics. We could not discern any asymmetry or pointing of the amplified lines, which is as expected for such a low gain-length product amplifier. The interesting electric quadrupole (E2) lines were unambiguously identified in both the streaked and time-integrated x-ray spectra. The intensities of the E2 lines were quite low and suffered fairly high backgrounds from the nearby allowed 3s–2p neon-like lines. This pointed out the need for a higher-resolution focusing-crystal spectrograph, of the so-called “von Hamos” design. We are developing such an instrument for fielding in the two-beam chamber in 1990.

Bright lasing was observed in germanium amplifiers irradiated at $9 \times 10^{13} \text{ W/cm}^2$ (1.5 times “nominal” irradiance) on all five neon-like lines (Fig. 3). As recorded by the SFFS, all amplified lines displayed emission characteristics seen before in selenium: very bright, short temporal duration ($\sim 250 \text{ ps}$ FWHM), and all positioned together very early in time (before noticeable spontaneous line or continuum emission). The axial MCP-IGS spectra gave no indication of any beam pointing or asymmetry, even for the longest-length targets (which is, to some extent, in contrast to our experience in selenium). Gains for the five lines were fairly easily measured (although the bright $J = 2$ lines required heavy filtering at the longer amplifier lengths) and are listed in Table 1. The x-ray spectra were dominated by neon-like $n = 3$ to $n = 2$ and $n = 4$ to $n = 2$ emission, which was as expected.

On examining the behavior of germanium amplifiers under varying

irradiances, we maintained a scaling relation between the target areal density and the irradiance. Using a fixed reference value of $30 \mu\text{g/cm}^2$ at $6 \times 10^{13} \text{ W/cm}^2$, we varied the areal density as the square root of the irradiance. Thus, at $2.4 \times 10^{14} \text{ W/cm}^2$ (a so-called 4 $\times$ target), the areal density was $60 \mu\text{g/cm}^2$, and so on. This was done to keep the pump laser “burn-through” condition centered in time to the peak of the pulse intensity, in accordance with the hydrodynamic calculations of London and Rosen.¹⁶ Table 2 illustrates the scope for this study, showing the 12 shot numbers distributed in irradiance-length space.

The first (and quite remarkable) result is that amplification in the XUV was observed for all shots in the matrix. The shots at 1.5 times nominal irradiance resulted in the brightest

amplified lines. Both of these results are similar in character to the British data, in which thick targets were shot single-sided at $1.06 \mu\text{m}$.¹⁴ Lasing similar to the nominal case but reduced in amplitude continued to be seen at two and four times nominal. However, at

Table 2. Matrix of the germanium ionization study.^a

Irradiance (6×10^{13} W/cm)	Length		
	2 cm	3 cm	4 cm
0.5		•	
1.5	•	•	••
2		•	••
4		••	
8	••		

^a Data points indicate number of Nova laser shots.

Figure 3. XUV spectrum from a long germanium amplifier shot at approximately $9 \times 10^{13} \text{ W/cm}^2$. These data are from the time-gated on-axis MCP-IGS spectrograph, with an instrumental resolution ($E/\Delta E$) of 1100. The gain has been deliberately set high to record the three weaker amplified lines. The two bright $J = 2$ lines at 23.2 and 23.6 nm are saturated (their intensity exceeds the instrumental dynamic range); on this same intensity scale, they would intrinsically be about four times brighter than recorded. The broad, low pedestal at the base of these bright lines is an instrumental artifact associated with detecting such intensities. The brightest spontaneous-emission line in the spectrum is the $2s_{1/2}$ – $2p_{3/2}$ Na-like line at 22.65 nm; it is barely discernible on the scale shown.

eight times nominal irradiance ($5 \times 10^{14} \text{ W/cm}^2$), we noted a dramatic and unexpected shift in the timing of the amplified lines. For this determination, the time-resolving character of the SFFS proved invaluable. Although there was no absolute timing fiducial on the streak camera, it was clear both from the onset of continuum and from the measured shot-to-shot jitter of the streaks that the $l = 2$ lines (the only lines visibly amplified) had shifted to later time and that, relative to the nominal-irradiance condition, the shift in peak ASE output

was $320 \pm 70 \text{ ps}$. This effect can be seen in the SFFS temporal lineouts in Fig. 4 and was clearly reproducible. Assuming that the nominal case was identical in absolute timing to that measured for selenium, the eight-times-nominal-case ASE peaks just as the pump laser turns off. This temporal behavior strongly suggests a recombination-dominated population kinetics.

It is also interesting and somewhat surprising that no fluorine-like lines have undergone ASE in the entire matrix, although fluorine-like

XUV lines may be present in the twice-nominal and higher-irradiance spectra. The analysis has been hampered somewhat because of $n = 2$ to $n = 2$ lines in L-shell ions detected in second order on the axial MCP-IGS. Different gratings and filtering, which will be used in our upcoming experiments in FY 1990, are expected to alleviate this problem at least partially. The x-ray spectra have shown that under four times nominal irradiance, the ionization balance is running well into the L-shell, with lines from ion species as stripped as boron-like visible.

Experimental Program for FY 1990

Clearly, our experiments in FY 1989 have just begun to address the experimental challenges associated with understanding these neon-like XUV amplifiers. We are planning an ambitious program for FY 1990 to more thoroughly probe the phenomena studied in 1989 and to expand the scope of the investigation to touch on some of the long-outstanding questions. We plan to measure the linewidth and line shape of the amplified XUV lines, in particular the $l = 0$. These measurements will test whether Dicke narrowing or other physics influencing line shape are present and whether they might be affecting macroscopically observed gains. To make the measurements, Lawrence Berkeley Laboratory researchers are developing a new instrument. This high-resolution XUV spectrograph will, like the SFFS, use varied-line-space grating to focus to an x-ray streak camera for time-resolved detection and will be placed in the on-axis location used by the SFFS.

Figure 4. Temporal lineouts of the 23.6-nm $l = 2$ line from 2-cm neon-like germanium amplifiers, recorded by the streaked flat-field spectrograph (SFFS). The black trace is from a shot of near nominal irradiance, about $9 \times 10^{13} \text{ W/cm}^2$. In the blue trace, the irradiance was about $5 \times 10^{14} \text{ W/cm}^2$, around six times higher. The peak of the XUV line intensity shifts by $320 \pm 70 \text{ ps}$. Some background line and continuum emission is seen (especially evident in the higher irradiance shot as a long-lived pedestal on which the lasing line sits) because of the low spectral resolution of the instrument.

Resolutions ($E/\Delta E$) of about 25,000 are expected.¹⁷ We will also try to replicate the results of Refs. 12–15 as a starting point for investigating $I = 0$ gains under different laser-matter couplings. A second major new effort will be made to produce purely recombinative lasers by means of short-pulse excitation. A new oscillator at Nova should provide 20-ps, 100-J pulses sufficient to drive mid-Z ions to or past the neon-like state. The dominant processes following this excitation would be recombinative at very high electron densities (since the plasma would not have had much time to expand), making them quite conducive for recombinatively fed XUV amplification. This type of experiment would effectively “force” the population kinetics into one predominant mode. An alternative experiment, also proposed for 1990, calls for long-pulse (>5 -ns) excitation of very thick “slab” targets in an effort to set up steady-state hydrodynamic and radiative conditions. Each of the two extremes of pulse length should be simpler in principle to model than the present conditions (perhaps better optimized for amplifier behavior) of 0.5-ns pulses and exploding foil geometry. From an experimental standpoint, we must measure the entire angular footprint from these sources because, in either case, the beam may not follow the mechanical geometry of the target. Therefore, we are modifying the on-axis MCP-IGS to incorporate a 60-mrad imaging fore-optics assembly

in front of the instrument (consisting of a cylindrical mirror and a turning mirror). With this modification (which is similar to a modification reported in 1987 by Whelan and coworkers¹¹), a measurement of the angular divergence of the beam can be made by collimating. Also, if it is of interest, we will be capable of forming a spectrally resolved, one-dimensional spatial image of the amplifier.

We will continue to study silver amplifiers. A major concern here is the development of a von Hamos high-resolution crystal x-ray spectrograph for distinct, uncompromised detection of the E2 lines for level population measurements. Also, we will study the interesting areal density scaling seen for silver. In germanium, we will continue to look for gain in fluorine-like lines. We have the pump power to shoot a 7.5-cm target at twice-nominal irradiance or a 4-cm target at four times nominal irradiance. Low gain lines may show up or they may not, resulting in yet another open question. We want to probe the irradiance conditions between the 4x and 8x cases to try to determine where and how the shift in amplifier timing occurs. To do this, we will set up absolute timing fiducials on all streaked instruments, in particular the SFFS, to accurately cross-check (to within a few tens of picoseconds) the XUV and x-ray emissions to the pump pulse. Finally, we will try to measure the

electron temperature in the amplifier plasma by admixing in some K-shell emitter such as aluminum.

Conclusions

The characterization of neon-like plasmas that act as XUV amplifiers involves several physical processes that interact to yield many interesting and sometimes unexpected results. It is a difficult exercise because clever experimental design and execution are needed to give insight into fundamental questions. We have taken up the challenge and have already found some interesting new phenomena; we will continue our experiments in FY 1990 with the anticipation of addressing a much more diverse array of issues.

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Shock-Driven Turbulence and Chunk-Formation Experiments on Nova

D. R. Slaughter and A. K. Harrison

This report describes a series of planned experiments in which we will study the growth of turbulence and possible formation of "chunks" (discrete regions of capsule-wall material) when a capsule of deuterium-tritium (DT) gas is imploded to produce fusion yield. Experimentally observed fusion yield is often substantially lower than computer predictions of yield based on one-dimensional simulations. The reduced yield arises from a variety of forces, such as nonuniform drive pressure, variations in wall density, and variations in thickness, which act to produce a nonuniform or aspherical implosion and unstable mixing of capsule-wall material into

the confined fuel. Such forces cool the plasma and reduce peak compression, with an ultimate reduction of fusion yield. The most familiar mechanism is the Rayleigh-Taylor (R-T) instability in which a heavy fluid is accelerated by a light fluid, resulting in growth of perturbations at the interface between them.¹ The growth rate increases with the ratio of densities in the two regions. Experimental study of this instability has been extensive in fluids at room temperature, in aerodynamic experiments, and in plasmas.²⁻⁵

High-intensity laser pulses generate a shock wave as a result of large ablative driving forces. As the shock propagates across an interface

between two media of differing density, the interface is impulsively accelerated, and surface irregularities grow in an unstable mode according to the Richtmyer-Meshkov (R-M) description.⁶ This instability mechanism is a special case of the R-T instability in that it is caused by a shock wave crossing the interface. The R-M mechanism is also observed experimentally (see Ref. 7 for a bibliography), and we believe that it may be important in some fusion capsules. Extensive modeling of R-M-induced turbulence has been done by Leith and others (see Ref. 8 for a bibliography). Many of the parameters in these models are based on fluid experiments at room

temperature with liquids and gases in shock tubes. Experiments at LLNL have begun to augment the experimental data base for R-M instabilities under thermonuclear plasma conditions.^{7,9}

Planned Experiments

Recent experiments on R-M-induced mix have focused on the spatial extent (scale length normal to the interface) to which dense material mixes with less-dense material. However, these studies did not investigate such phenomena in more than one dimension and did not seek to identify chunks. Our planned experiments are directed toward studying large-scale turbulence in the form of jets or chunks generated at an interface. We intend to characterize the size and frequency-of-occurrence distribution of discrete volumes of dense material (chunks) formed, however briefly, within a less-dense region by R-M processes.

We will expose targets, including a low-density foam and a high-density solid, to intense x rays generated by the Nova 100-kJ beams. Ablatively driven shocks will be generated in targets with nominal dimensions of $0.1 \text{ mm}^2 \times 1000 \text{ }\mu\text{m}$. We anticipate that plasmas generated in this way will reach temperatures on the order of 100 eV and have densities somewhat less than solid (typically $\leq 10^{21} \text{ cm}^{-3}$). We will study various foil pairs and will include variations in density, drive, and preheat conditions.

We are evaluating three complementary experimental techniques, any or all of which may be used if and when chunks are observed. The candidate techniques are:

- Direct observation of density nonuniformities by x-ray shadowgraphy using a soft x-ray backlight source and a Wolter microscope or pinhole camera for image recording,

- Computed x-ray tomography using an array of backlight soft x-ray sources and pinhole-imaging detectors to construct a three-dimensional (3D) image of density perturbations and turbulence.
- Thomson scattering of light from chunks to determine the Fourier transform of their density distribution.

Imaging. Plasma turbulence and chunk formation may be observed by backlighting plasma with a source of soft x rays and observing variations in plasma opacity due to density fluctuations. In this case, the viewing axis along which opacity is determined may be either perpendicular to the interface (parallel to shock propagation) or oblique, providing viewpoints for observation of different modes. This type of measurement determines only the areal density along a line through the plasma and may fail to detect or quantify turbulence unless there is mass motion perpendicular to the viewing axis. Consequently, a variety of viewing axes is desirable to determine the magnitude and spatial scale length for turbulence in various modes.

We will image opacity variations resulting from turbulence and chunk formation using either pinhole or Wolter microscope¹⁰ imaging devices to determine the spatial pattern of opacity and the magnitude of density fluctuations. The Wolter microscope has a spatial resolution of about $10 \text{ }\mu\text{m}$ and effective solid angle referred to the object of about 10^{-8} sr . Experiments using the microscope have been carried out at Nova previously (Dave Munro and Gail Glendinning, Lawrence Livermore National Laboratory, private communication, 1989). Alternatively, we have deployed pinhole x-ray-imaging devices of nominally $10\text{-}\mu\text{m}$ resolution, which have the same effective acquisition solid angle and are much

simpler to install and operate, but lack the narrow-band spectral acceptance of the Wolter microscope. Simulations are under way to estimate the magnitude of opacity variation for reasonable predictions of turbulence and to determine whether the modulations in transmitted x-ray signal are sufficiently large and will provide sufficient contrast against the background of both transmitted and scattered x-ray radiation. This experimental approach should provide data on spatial scale length for chunks larger than $10 \text{ }\mu\text{m}$.

Computed Tomography. To observe density fluctuations due to turbulence, we may need to obtain 3D images of the plasma density. One way of obtaining such data is to use the established technique of computed tomography. A rich literature describes advanced techniques for observing small modulations in material density using backlight-opacity data. In general, this is a very difficult measurement, requiring each volume of interest to be probed from many directions to unfold the scattering and attenuation contributions along the radiation paths connecting those volumes to the backlight source and detector. Many images from many viewpoints are required for detailed projection of the density distribution. However, crude images may be obtained with as few as five views, as has been demonstrated on inertial confinement fusion plasmas. Some useful data, although not a computed tomograph, may be obtained on scale lengths with even fewer views. We are studying computed tomography for later use and are evaluating its efficacy using simple simulations. At the very least, computed tomography would require the development of additional backlight sources and an array of pinhole-imaging devices.

Thomson Scattering. Light-scattering techniques have been used for many years to determine the size distribution of small particles suspended in aerosols and liquids by analysis of Rayleigh, Mie, or other scattering processes.¹¹ Incoherently scattered light may also be used to determine the spatial scale length of turbulence or chunk formation in a plasma.¹²

A probe beam is not scattered by a uniform plasma; instead, it is scattered by density fluctuations within it. The angular distribution of the scattered light yields directly the spatial Fourier transform of the plasma, i.e., the spatial distribution of electron-density fluctuations, as follows:¹²

$$\frac{d^2 p}{d\lambda d\Omega} \approx s_0 S(k, \lambda). \quad (1)$$

In Eq. (1), s_0 is a constant that depends on the probe beam, and k is given by:

$$k^2 = k_i^2 + k_s^2 - 2k_i k_s \cos \theta, \quad (2)$$

where k_i and k_s are the incident and scattered wave numbers ($k = 2\pi/\lambda$), respectively, and θ is the scattering angle. The term $S(k) = |F(k)|^2$ is the square of the Fourier transform of electron density. The value of S may be determined experimentally by sampling the angular distribution of scattered power.

Small-angle scattering from high-density plasmas may be coherent if the wavelength is comparable to or larger than the Debye length,¹² which will be effectively the form of $S(k)$. Anticipated temperatures and densities include plasma conditions where coherent effects may be important. However, the experimental measurement techniques employed and the feasible measurement limits are the same whether or not the scattering is coherent.

In practice, $S(k)$ can be determined only approximately because of the limited number of measurement points and uncertainties at each point. As a result, we cannot obtain an unambiguous spatial distribution. Instead, a model of the

turbulence must be compared to the transform data, and model parameters must be adjusted for an optimum fit. Any conclusions are limited by the quality of the model and the fit to the data.

In addition to these difficulties, a fixed laser wavelength (fixed k_i and k_s) limits the determination of S to a relatively narrow range, $0 < k < 2k_i$. The upper bound on k sets a practical limit of about 0.1 probe wavelengths on the smallest particles that can be characterized. At the other extreme, scattering is predominantly forward, so the minimum accessible scattering angle sets a lower bound on the measured k and a corresponding upper bound on the particle size that can be measured.

This situation may be understood intuitively by examining the Fourier transform of a step function of radius $r = a$ centered at the origin:

$$|F(k, a)|^2 = \frac{2}{\pi} \left(\frac{\sin ka}{ka} \right)^2, \quad (3)$$

which is plotted as a function of scattering angle in Fig. 1. The figure suggests that characterization of particles whose radii p are larger than a few wavelengths requires good-quality measurements at small angles (< 10 deg). Such characterization is difficult because the probe beam is up to six decades more intense than the Thomson-scattered signal and produces large background intensities of unscattered light or light scattered in locations other than the sampled volume of plasma. Similarly, particle sizes of less than a few tenths of the probe-beam wavelength result in angular distributions that are nearly constant. Thus, useful characterization of chunk size by Thomson scattering is practically

Figure 1. Fourier transform (squared) of a step function located symmetrically about the origin. Curves are for various spatial extents of the step function (radius p) in multiples of the probe wavelength.

limited to the range of about 0.3 to 10 wavelengths of the probe beam. Available probes are in the wavelength range of 0.35 to 1.0 μm .

Measurement uncertainties are aggravated by the very small Thomson-scattering cross section, which is given by:¹³

$$\frac{d^2P}{d\lambda d\Omega} = I_0 \left[\frac{r_e^2 n_e}{2\sqrt{2\pi\lambda_0 \sin \frac{\theta}{2}}} \times \left(\frac{m_e c^2}{kT} \right)^{1/2} e^{-\frac{m_e c^2}{8kT} \left(\frac{\lambda - \lambda_0}{\lambda_0 \sin \theta/2} \right)^2} \right], \quad (4)$$

where I_0 is the incident laser intensity, r_e is the classical electron radius, n_e is electron density, λ_0 is the wavelength of the probe laser, θ is the observation angle relative to the probe, m_e is the electron mass, T is the electron temperature, and λ is the wavelength at which scattered light is observed. A single Nova beam may be used as a probe for Thomson-scattering experiments to deliver incident power up to 10^{14} W/cm^2 at 350 nm. Note that the spectral width of the scattered light is a function of scattering angle so that, although the total amount of light scattered is independent of angle, the differential intensity is greatest in the forward direction. In a practical experiment, a larger linewidth reduces the signal-to-background ratio so that very narrow and highly peaked spectra at forward angles are preferred. For a 100- μm -thick plasma of density 10^{21} cm^{-3} , the scattered intensity is about 5×10^{-7} of the probe intensity and varies in proportion to the

electron density. A single 100- μm -diam chunk scatters about 5 kW of light, or about 10^{10} photons/ps. Detection efficiencies larger than about 10^{-9} will provide adequate statistics for the experimental conditions in this example.

Several potential experimental problems may restrict the range of plasma parameters amenable to investigation using Thomson scattering. First, at high plasma densities, the wavelength of the probe beam is too long to penetrate and is simply reflected from the critical plasma surface. Such reflection occurs when the plasma frequency equals that of the probe beam. The critical density is given by:

$$n_c = \frac{\pi m_e c^2}{e^2 \lambda^2}. \quad (5)$$

For a probe beam with wavelength $\lambda = 350 \text{ nm}$, the critical density is $9 \times 10^{21} \text{ cm}^{-3}$. Second, potential background interferences may be caused by bremsstrahlung radiation within the plasma and thermal radiation from its surface. Bremsstrahlung radiation intensity is given by:¹⁴

$$\frac{d^2P}{d\lambda d\Omega} = \frac{8gr_e^2 c \alpha}{\sqrt{6\pi}} \left(\frac{m_e c^2}{kT} \right)^{1/2} \times E_v \frac{n_e^2 Z}{\lambda} e^{-\frac{E_v}{kT}}, \quad (6)$$

where g is the gaunt factor, α is the fine structure constant, and E_v is the photon energy. Because the bremsstrahlung radiation generated per unit volume is proportional to the square of density, while the scattered signal increases linearly with density, this interference may

become important at the highest plasma densities. Thermal radiation may be assumed to be blackbody given by the Planck distribution:

$$\frac{d^2P}{d\lambda d\Omega} = \frac{2hc^2 \lambda^{-5}}{e^{\frac{hc}{\lambda kT}} - 1}, \quad (7)$$

where h is Planck's constant.

Scattered intensity is plotted as a function of plasma density for several temperatures in Fig. 2 to place the Thomson-scattered light signal in proper perspective for various plasma conditions. In this figure, the experiment geometry is assumed to be a 200- μm -diam sphere. For comparison, the interfering intensities resulting from thermal and bremsstrahlung radiation are also plotted. Examination of the figure shows that reasonably good signal-to-background ratios should be attainable in the plasma electron-density range of 10^{19} to 10^{22} cm^{-3} .

The five-channel spectrometer under construction for Nova experiments will allow us to measure the angular distribution of Thomson-scattered light at five points. Our estimates given above indicate that we should have sufficient scattered intensity to measure the angular distribution at five angles less than about 10 deg, provided that background due to the much more intense probe can be suppressed. These measurements may provide useful data on the scale length of chunks in the range of 0.3 to 3 μm . However, the chunks must have an electron density that is distinct from that of their surroundings. Simulations indicate that electron densities in chunks decay with time until they approach the density of the surrounding medium.

Summary

In experiments soon to begin at the Nova laser facility, we will study the time evolution of turbulence and chunk formation in laser-driven plasmas in the R-M regime. The design of experiments and evaluation of diagnostic techniques are in progress, and we are studying several promising experimental approaches in detail. In our first experiments, we expect to employ simple pinhole imaging or will use the Wolter microscope to observe chunks larger than about 10 μm . This technique has

been used previously in R-T-growth experiments and can be considered to be mature. We may then extend subsequent measurements to multiple-axis imaging to obtain some degree of multidimensional data on chunks. In addition, we may ultimately use computed tomography to study the evolution of chunk size and shape. Finally, we may use Thomson scattering to observe the smallest chunks in the range of 0.3 to 3.0 μm . However, we anticipate that this last technique will be difficult to employ in Nova experiments.

Figure 2. Signal power at 350 nm vs plasma density. Plasma is assumed to be a 200- μm -diam sphere uniformly illuminated by 10^{14} W/ cm^2 of 350-nm light. Curves show peak Thomson-scattered light at 350 nm compared to internally generated bremsstrahlung light and surface thermal radiation at the same wavelength. Estimates are shown for plasmas at temperatures of 20, 100, and 500 eV.

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Opacity of Ionized Materials: Nova Laser Experiments

T. S. Perry

The x-ray opacities of highly ionized materials can be vastly different from their cold opacities. A material may become nearly transparent at some photon energies and increase in opacity by orders of magnitude at others. Knowing how the opacity of materials changes with ionization is of fundamental interest for nuclear weapons design and astrophysics, and for the study of laser-produced and magnetically confined plasmas.

Until recently, the only available information on the opacity of

highly ionized materials was from theoretical calculation. Experimental data were limited to systems of atoms only one or two times ionized. A program was undertaken a few years ago at the Nova laser to provide experimental data on the opacity of highly ionized materials. This effort has been a collaboration between LLNL's NTES, Nuclear Design, and Lasers programs and the Atomic Weapons Establishment in Great Britain. During FY 1989, the techniques that have been developed in that

program have successfully produced previously unavailable opacity information.

Experiment

The basic experimental procedure used to date for obtaining opacity information is the technique of point-projection spectroscopy,^{1,2} shown in Fig. 1. A point source of x rays is used as a backlighter to produce a two-dimensional radiograph of the sample. Reflecting this image with a Bragg x-ray crystal gives spectral information in one

Figure 1. Point-projection spectroscopy obtains the absorption, backlight intensity, and self-emission in one shot. I_0 is the unattenuated backlighter spectrum, and τ is the material absorption coefficient from which the opacity is derived.

Figure 2. Film record of an aluminum opacity experiment, illustrating the capabilities and difficulties of the experiment. The dark vertical lines are absorption lines from highly ionized aluminum. The black horizontal lines, caused by a support structure in front of the film, provide a reference for subtracting film fog. The grey horizontal stripe in the middle of the film is from a filter containing aluminum, silicon, and yttrium; the x-ray absorption edges in these materials provide fiducials for calibrating the wavelength scale. The bright spots on the right were caused by debris from the sample breaking through the light filter in front of the film. Irregular vertical and diagonal lines arise from defects in the Bragg diffraction crystal.

Figure 3. Streaked image of an exploding foil. The density at any time is determined by assuming uniform density and measuring the width of the expanded foil. At late times, one side of the sample collides with its supporting frame, causing the expansion of the sample to be reversed. This can be seen at the right side of the streaked image, where the boundary marking the top edge of the sample begins to slope downward.

direction. Because of the imaging, this technique can record the backlighter spectrum, the x-ray absorption in the sample, and the sample emission on every shot. The opacity can then be determined by subtracting sample emission and dividing the absorption spectrum by the backlighter spectrum. The sample is ionized by heat from eight of Nova's ten laser beams. Each of the eight beams delivers 2 kJ of blue light in a 1-ns-long pulse. The point backlighter is heated by the other two beams, each of which typically delivers 200 J of blue light in a 100-ps pulse.

To verify the experimental method, we conducted our initial experiments on aluminum, a simple atomic system that can be calculated to a high degree of accuracy. Because the number of energy levels is small, they can all be included explicitly. So far, our results have shown good agreement with theory,^{3,4} but they also indicate several areas where experimental methods need to be improved. Figure 2 is an example of the raw data obtained from these experiments.

Temperature and Density

To make meaningful comparisons between theory and experiment, we must know the temperature and density of the sample. To some extent, hydrodynamic calculations can be used to predict these factors, but the accuracy of an experiment will always be in doubt unless temperature and density can be experimentally determined. The density of the samples has been measured this last year by the Wolter 22x microscope⁵ that is mounted on the Nova chamber. As the sample expands, a streak camera mounted on the microscope records the

sample thickness as a function of time. Figure 3 is a film image from one of these experiments. We can determine the dependence of the opacity on density by firing the backlighter at different times.

We measured the temperature of the sample by using the Dante instrument⁶ on the Nova chamber. This instrument uses K- and L-edge filtered diodes to measure x-ray emission spectra between 0.1 and 3 keV. The total x-ray energy of the emission is then used to infer a temperature, and its spectral shape can be used to determine whether the x-ray emission is Planckian, as would be expected for a sample in thermal equilibrium. By comparing

the measured temperatures and densities with the hydrodynamic calculations, we have obtained good measurements of the temperature and density to use with the measured opacity data.

Now that the techniques for measuring opacity, density, and temperature are working, we are measuring materials that are more complex than aluminum. Because of the large number of energy levels in these materials, we make several approximations in theoretical calculations of opacity. The Nova opacity experiments now under way will provide the first data for checking the validity of these approximations.

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Ionization Balance Studies of Hydrogen- and Helium-Like Species Created with a 20-ps Laser Heating Source

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Recombination-driven, soft x-ray population inversions are of interest to the laser, plasma, and x-ray physics communities. Understanding the ionization balance and the plasma dynamics of recombining systems can provide useful information about atomic-level population kinetics as well as suggest a useful technique for achieving short-wavelength (below 4.5 nm) soft x-ray lasing. The

ionization balance studies discussed here were done using high-density (10^{20} to 10^{21} e/cm³), highly ionized (>50% bare, hydrogen, and helium-like) plasmas created by heating aluminum and magnesium-fluoride foils with 20-ps green ($\lambda = 532$ nm) laser light focused to intensities of 5×10^{14} to 1×10^{15} W/cm². The plasma electrons cool rapidly as a result of hydrodynamic expansion, creating a plasma with ions that

greatly deviate from thermodynamic equilibrium. The low-temperature electrons recombine with the ions by preferentially filling the states with a higher principal quantum number ($n \geq 2$), allowing population imbalances between high metastable Rydberg states and lower-lying levels.

When we compared the pertinent atomic-rate coefficients, we found

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that the physical processes involved with populating the upper Rydberg levels of the resonance transitions became more transparent.¹ In the hydrogen-like ions, the upper Rydberg levels are populated

by collisional excitation of the hydrogen-like ions, radiative recombination of bare ions, and three-body recombination of bare ions. For this simple illustration, cascading is ignored. The rate coefficients

corresponding to the remaining processes are expressed as²

- Collisional excitation (in $\text{cm}^3 \cdot \text{s}^{-1}$):

$$\alpha_{\text{CE}_{nm}} = 6.4 \times 10^{-8} \left(\frac{n}{Z} \right)^3 \times \chi_n^{1/2} \left(\frac{m^2}{m^2 - n^2} \right) f_{nm} \times \exp(\chi_m - \chi_n). \quad (1)$$

- Radiative recombination (in $\text{cm}^3 \cdot \text{s}^{-1}$):

$$\alpha_{\text{RR}_n} = 5.2 \times 10^{-14} \times Z \chi_n^{1/2} \Phi(\chi_n). \quad (2)$$

- Three-body recombination (in $\text{cm}^6 \cdot \text{s}^{-1}$):

$$\alpha_{\text{TBR}_{nm}} = 5.6 \times 10^{-31} \left(\frac{m}{Z} \right)^6 \times \chi_n^2 m^2 [1 - \Phi(\chi_m)]. \quad (3)$$

In these equations, n and m are the lower and upper atomic levels, respectively; Z is the atomic charge; $\chi_n = 1.6 \times 10^5 Z^2 (n^2 T)^{-1}$ (where T is temperature in Kelvins); f_{nm} is the hydrogenic oscillator strength; and $\Phi(\alpha) = \alpha \exp(\alpha) E_1(\alpha)$ (where E_1 is the exponential integral). In the short-pulsed laser-produced plasma experiments, once the heating laser turns off, the electrons quickly cool. The low electron temperature serves to significantly reduce the effect of collisional excitation on populating the upper Rydberg levels. Furthermore, as a result of the

Figure 1. Comparison of atomic rate coefficients at $N_e = 10^{20} \text{ cm}^{-3}$.

n_e^2 dependence, the three-body recombination rate becomes the dominant populating mechanism at high densities. The three-body recombination rate increases with principal quantum number n , thereby preferentially populating upper Rydberg states. The effect is illustrated by comparing the atomic rate coefficients for an electron density $N_e \approx 10^{20} \text{ cm}^{-3}$ in Fig. 1.

Experimental Apparatus

The experiment was conducted using the Chroma laser facility at KMS Fusion, Inc., in Ann Arbor, Michigan. The Chroma laser facility is a Nd:YAG system that produces up to 500 J at $\lambda = 532 \text{ nm}$ in two 1-ns beams. For these experiments, the Chroma amplifier chain was used in conjunction with a 20-ps full-width-at-half-maximum mode-locked oscillator, producing a maximum of 10 J at $\lambda = 532 \text{ nm}$ in two beams. Each laser beam was focused using an $f/6.0$ lens, producing laser intensities of up to $2 \times 10^{15} \text{ W/cm}^2$. We measured the temporal characteristics of the pulse before each shot using an autocorrelation technique and during each shot by focusing the leakage through a turning mirror onto the photocathode of a fast optical-streak camera. The accuracy of these measurements was believed to be $\approx 1 \text{ ps}$. On each shot, we monitored the spatial characteristics of the beam by using an equivalent-plane off-line focusing system, which focused leakage through the final turning mirror located in front of the chamber entrance onto a charge-coupled device (CCD) camera. The information was stored digitally and analyzed with image-processing software.

Diagnostics

We used four diagnostics to analyze the short-pulsed laser-produced plasmas: (1) a spatially integrated temporally resolved x-ray spectrograph, (2) four-frame holographic interferometry, (3) filtered visible photodiodes, and (4) a temporally integrated x-ray pinhole camera.

Spectroscopic data were collected using a Kentech x-ray streak camera in conjunction with a potassium hydrogen phthalate (KAP) crystal as an energy disperser. A $2.5\text{-cm} \times 500\text{-}\mu\text{m} \times 1\text{-mm}$ brass slit was placed 1 mm in front of the x-ray streak-camera photocathode to baffle the plasma x rays. The visible and vacuum ultraviolet emission was filtered using a $12.5\text{-}\mu\text{m}$ beryllium filter in front of the slit. The x-ray streak camera was operated at a temporal dispersion of 54 ps/mm , providing temporal resolution of $\approx 27 \text{ ps}$. We estimated the energy resolution using:

$$\frac{\Delta E}{E} \approx \frac{\Delta x}{l} \cot(\theta_B), \quad (4)$$

where Δx is the plasma size ($\approx 200 \mu\text{m}$), l is the source-to-photocathode distance (14 cm), and θ_B is the Bragg x-ray diffraction angle ($\approx 18 \text{ deg}$). Thus, the estimated resolution is $\Delta E/E \approx 4.4 \times 10^{-3}$. This allowed all pertinent resonance line data to be collected while providing sufficient spectral coverage to obtain hydrogen-like free-bound continuum data.

A four-frame holographic interferometer was used to determine the electron density.³ The interferometer light source was produced by splitting and separately amplifying part of the 20-ps heating laser pulse. After amplification, the laser pulse was frequency quadrupled ($\lambda = 262.5 \text{ nm}$), further split into four beams, and propagated through the plasma to produce the interferograms. The spacing between the pulses could be set as short as 75 ps or as long as 250 ps, allowing density data to be collected early as well as late in the plasma lifetime.

Figure 2. Typical x-ray streak spectrograph data from aluminum targets.

Calorimeters, calibrated filtered visible photodiodes, and a time-integrated x-ray pinhole camera were used to measure both energy absorbed in the target and heating uniformity. The absorbed energy was measured by determining the difference between the energy on target and the reflected energy. The energy on target was measured using a 4% beam splitter (located behind the final reflecting surface)

and a calibrated calorimeter. The reflected energy was taken into account by spacing a series of calibrated and filtered visible photodiodes around the target and measuring the angular-dependent reflected laser energy. The measured values were integrated and then subtracted from the energy on target to give the absorbed energy. A 125- μm beryllium-filtered time-integrated pinhole

camera was used to monitor heating uniformity.

We used two K-shell-emitting elements in the ionization balance study, pure aluminum and magnesium doped with fluorine (MgF_2). The geometries used for the aluminum targets were a 1-mm slab, a thin foil (60-, 120-, and 240-nm-thick) coated on a 300-nm-thick Formvar ($\text{C}_2\text{H}_7\text{O}_2$) sheet, a 100- μm -diam, 200-nm-thick microdot sandwiched between 50-nm-thick Lexan (CH) sheets, and a 120-nm-thick freestanding sheet. We used two MgF_2 target geometries, a 1-mm-thick slab and a 100- μm -diam, 200-nm-thick microdot sandwiched between two 50-nm-thick Lexan sheets. The sandwiches were mounted on 700- μm -outside-diam $\times$ 500- μm -inside-diam $\times$ 7- μm -thick Lexan washers. The remaining targets were mounted on 1400- μm -outside-diam $\times$ 1200- μm -inside-diam $\times$ 7- μm -thick copper washers.

Analysis and Results

The data from the x-ray streak spectrograph were digitized, and the photocathode response, crystal response, and beryllium-filter transmission were folded into the data. Also, to correct a "pincushion"-type time-shift distortion caused by a streak camera, we assumed that the peak continuum intensity between resonance lines occurs at the temporal peak in laser intensity. Using these assumptions, we took spectra averaged in 27-ps intervals.

We analyzed the data by applying the quasi-steady-state approach,^{4,5} which assumes that an equilibrium has been achieved between level populations (as a result of the short equilibration times) despite the fact that the ionization states are not in equilibrium. By fixing the relative concentration of the fully stripped

Figure 3. (a) Ionization balance time history of fully stripped and hydrogen-like ions. (b) Relative percentages of bare and hydrogen-like ions.

and hydrogen-like ground-state populations, we solved the rate equations for the excited-state population densities, yielding a parameterized spectrum. The parameterized spectrum is fitted to the observed data by minimizing the χ^2 between several lines in the predicted spectrum and the data.⁶ Using the slope of the free-bound continuum to measure the temperature,⁷ the parameterized spectrum predicts the optimum electron density and ionization balance between the fully stripped and hydrogen-like ions for which the χ^2 is minimized. The procedure was applied to the high- n lines to reduce the effects of opacity.

Using this approach, we analyzed data from a 1200-nm-thick aluminum foil backed with 3000-nm-thick Formvar targets (see Fig. 2). The target was heated with $1 \times 10^{15} \text{ W/cm}^2$ on the aluminum side and 6×10^{14} on the Formvar side. A plot of the relative ion percentage of bare/(bare + hydrogen-like) is displayed in Fig. 3 with the ionization balance time history of fully stripped and hydrogen-like ions. Once the laser intensity is off and the electron temperature cools to $\approx 150 \text{ eV}$ (time $t \geq 100 \text{ ps}$), further production of fully ionized aluminum is negligible. The fraction of fully ionized aluminum rapidly decreases as a result of the production of hydrogen-like ions via recombination. Likewise, the fraction of hydrogen-like ions decreases from recombination into helium-like ions. By comparing the time-dependent, peak resonance line intensities, we can infer the charge-state population distribution of a given ion. A plot of the time-dependent hydrogen-like line intensities shows a period during which the $1s(2S_{1/2})-3p(2P_{1/2,3/2})$ ($\text{Ly}\beta$) intensity is greater than the

Figure 4. Time-dependent resonance line intensities of (a) helium- and (b) hydrogen-like ions.

$1s(2S_{1/2})-2p(2P_{1/2,3/2})$ (Ly_{α}) intensity, suggesting a population inversion between metastable states in the $n = 3$ manifold and lower-lying levels in the $n = 2$ manifold produced by the recombining fully stripped ions (see Fig. 4). Similar $n = 3$ to $n = 2$ inversions are suggested in the helium-like ion fraction by comparing the time-dependent $1s^2(^1S_0)-1s3p(^1P_1)$ (He_{β}) to the $1s^2(^1S_0)-1s2p(^1P_1)$ (He_{α}), apparently as a result of recombination of hydrogen-like ions. We are continuing the analysis so we can fully understand the implications of these effects.

Conclusions and Plans for FY 1990

We have studied the ionization balance of fully stripped and hydrogen-like aluminum ions in plasmas produced by short-pulse lasers. The plasma electrons rapidly cool, recombining with the ions by preferentially filling the upper Rydberg states of resonance transitions. We analyzed the data using the quasi-steady-state model, which uses the measured temperature to predict the x-ray spectrum. We then compared the parameterized spectrum to the measured data, and by minimizing the χ^2 between several predicted and measured line intensities, we determined an optimum electron density along with the ionization balance. Population inversions were inferred between metastable states in the $n = 3$

manifold and radiatively depleted states in the $n = 2$ manifold by comparing the $1s(2S_{1/2})-3p(2P_{1/2,3/2})$ to the $1s(2S_{1/2})-2p(2P_{1/2,3/2})$ transitions in aluminum targets.

In future experiments, we want to conduct a comprehensive gain study using the hydrogen-like magnesium population inversions (with particular emphasis on the $n = 3$ manifold to $n = 2$ manifold gain) while simultaneously measuring the plasma parameters using the K-shell spectra. In addition, we plan to measure the time-dependent helium- and lithium-like satellite lines to Ly_{α} and He_{α} , respectively, in high resolution ($E/\Delta E \geq 1000$), and design a high-gain, spatially and temporally resolved spectrometer to study the detailed behavior of the x-ray emission from short-pulsed laser-produced plasmas. To this end, we have scheduled a preliminary set of 20-ps experiments at the Nova two-beam facility. During these experiments, we will make our first attempt to observe gain produced by the hydrogen- and helium-like population inversions in magnesium. Along with the gain measurements, the K-shell spectrum will be used to characterize the plasma conditions in a lasing environment. Finally, the initial series of recombination-driven neon-like experiments will begin.

Our emphasis will be to better understand the physics of dense, recombining plasmas. Spectroscopic

resolution of these lines should provide a useful diagnostic of short-pulsed laser-produced plasmas because of the temperature sensitivity of the helium- and lithium-like satellite lines.⁸ Spatially and temporally resolved diagnostics will reduce the uncertainty of the role of gradients in the spectral features.

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A Test of Newton's Inverse-Square Law of Gravity

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Three centuries ago, Sir Isaac Newton proposed the law of gravitation. This law states that every two particles of matter in the universe attract each other with a force that acts along the line joining them, and that the magnitude of this force is proportional to the product of the particle masses and is inversely proportional to the square of the distance between them. This law is often called the inverse-square law of gravity.

Since its conception, Newton's law of gravity has withstood exhaustive testing in the laboratory with small masses and on the planetary scale with natural and man-made satellites. Until recently, however, it had not been tested in the intermediate range from 10 m to 10 km. This distance range is of particular interest because grand unification theories, which seek to unify the force of gravity with the three other fundamental forces (strong interactions, electromagnetism, and weak interactions), have suggested that Newton's law may break down in the intermediate range.¹ The effects of such a breakdown would be small, but observable, using modern equipment. If Newton's law were observed to break down, such a finding could have important implications to many programs and to fundamental theories of physics. For example, the trajectories of missiles would be different than those currently expected.

Many experiments have been conducted in the past century to search for instances of non-Newtonian gravity (i.e., gravitational behavior that departs from that predicted by

Newton's law). These experiments have been mostly of two types: composition-dependent tests, and distance-dependent tests.

In the first type of experiment, scientists search for a dependence of the gravitational force on the type of material, not just its mass. The most famous experiment in this category was done in 1922 by Eötvös and coworkers,² who placed equal masses of different materials on a torsion balance. The motion of the balance shows whether the gravitational force is the same between each material and the earth. Eötvös claimed to observe no discrepancy from Newton's law of gravity for many materials. However, in 1986, the experiment was reanalyzed by Fischbach and coworkers,³ who claimed that there was, indeed, evidence for non-Newtonian gravity, which would suggest the existence of another fundamental force, a "fifth force." This claim motivated many new experiments, the most precise of which was conducted in 1987 by Stubbs and Adelberger.^{4,5} These researchers found no evidence for a composition-dependent fifth force within the sensitivity limits of their instruments. At present, the conflicting results of these experiments have not been fully explained.

In the second type of experiment, scientists search for a deviation from the inverse-square law in the distance dependence of the gravitational force. This type of search is done by measuring gravity at different locations down a borehole or up a tower and then by comparing the measurements with predictions obtained with Newton's law.

For borehole experiments, the predictions depend on knowledge of density variations in the earth. For tower experiments, the predictions are obtained from measurements of gravity on the surface of the earth around the tower; thus, knowledge of the earth's density distribution is not needed.

Borehole vs Tower Experiments

Stacey and coworkers⁶⁻⁸ have conducted many borehole experiments in the past 10 y. Their most famous experiment, conducted in a deep Australian mine, led them to conclude that there is a repulsive, intermediate-range interaction with a strength of about 1% that of Newtonian gravity and that this interaction decreases exponentially with a range of about 200 m. However, other more recent experiments do not agree with the magnitude of the interaction or even on whether the proposed interaction is attractive or repulsive.

We performed an experiment similar to that of Stacey and coworkers in boreholes at the Nevada Test Site (NTS) and found a discrepancy between measured and calculated gravity⁹ that is five times greater than Stacey's results. The difference between the measurements obtained in Australia and Nevada results from the different density structures beneath the experimental sites and points to an inherent problem for borehole experiments as tests for non-Newtonian gravity. The problem is that the gravity predictions for a borehole experiment require knowledge of the density of the

Figure 1. The BREN tower at the Nevada Test Site is the location of our gravity test. This tower is nearly 465 m high, more than 20 m taller than the Sears Tower or the Empire State Building. The BREN tower is far from operating machinery or other buildings that could cause vibrations or produce electrical interference, and the long lines of sight over the flat, treeless desert allow us to locate and measure a dense grid of gravity stations on the ground surface.

earth both in the locality of the borehole and also deep below the bottom of it. Density is usually not well known below a borehole.

Geophysicists have known for many years that the earth exhibits density anomalies. In fact, areal surveys detecting and measuring such anomalies are used to prospect for mineral deposits. It is extremely difficult, at best, to predict gravity in a borehole accurately enough to allow for a test of the inverse-square law of gravity.

In a tower experiment, however, the difficulties encountered in borehole tests can be avoided. Predictions of gravity on a tower do not depend on estimates of the earth's density variations, but rather on measurements of gravity at many locations on the ground around the tower and out to a large distance. Thus, this technique accounts for density anomalies at all depths. (In mathematical terms, the important difference between a tower and borehole experiment is that in a tower experiment, we must solve Laplace's equation for the gravitational field in a source-free region, whereas in a borehole experiment, we must solve Poisson's equation for the gravitational field in the midst of sources that must be well understood.) Therefore, a tower experiment can provide unambiguous results. Of course, the quality of tower gravity predictions depends on the quality of the ground gravity measurements. Such measurements must be numerous, properly spaced around the tower, and sufficiently accurate.

Search for Non-Newtonian Gravity at the BREN Tower

We are conducting an experiment at the Bare Reactor Experiment Nevada (BREN) tower at the NTS. The BREN tower (Fig. 1) is 465 m

tall, 22 m higher than the Sears Tower in Chicago. It was built in 1962 to support a reactor that has since been removed, leaving a stable tower for making gravity measurements. The tower has an elevator that can stop at 11 platforms about 42 m apart. It is not used for broadcasting; thus, no electrical interference can affect instruments used for gravity measurements. In addition, the area around the tower is accessible and clear of obstructions, allowing for easy surface measurements. Of great importance to our experiment is the fact that an extensive, high-quality gravity data base for the area has already been accumulated as part of the nuclear-testing and nuclear-waste-isolation programs at the NTS. These features make it possible for us to conduct the most sensitive search to date for distance-dependent deviations from Newtonian gravity.

We are conducting our experiment in two phases. In the first phase, which is now completed, the experiment had sufficient sensitivity to detect a deviation of 1 part in 10^7 between measured gravity and the Newtonian prediction. In the second phase, which is now in progress, the experimental sensitivity is three times better (3 parts in 10^8).

We obtained measurements of gravity at ten locations on the tower using LaCoste-Romberg gravity meters. A gravity meter is essentially an accurate balance that measures relative changes in the earth's gravity (Fig. 2). We first measured the gravity (actually, the acceleration of gravity on a reference mass) on the tower relative to the gravity at the base of the tower. We then measured the gravity at the base of the tower relative to two gravity stations established by the U.S. Geological Survey (USGS) nearby. Each measurement was accurate to

about 1 part in 10^8 of the earth's gravitational field. At this level of accuracy, we must make certain that systematic errors are not introduced. For example, the effect of the moon's gravity must be removed. The instrument must be carefully calibrated, and instrumental drift must be measured and removed. In addition, because tower vibrations could affect the gravity meter, we took tower data only when the wind speed was less than 5 km/h.

We calculated the predictions of gravity on the tower on the basis of measurements of gravity on the earth's surface around the tower out to a 300-km radius. For the region within 4 km from the tower, we measured gravity at 823 locations on a grid, shown in Fig. 3. Ninety of these locations, shown as triangles in the figure, were included in the first phase of the experiment. In the region between 4 and 10 km, we are measuring gravity (second phase of the experiment) at about 60 additional locations chosen to complement the gravity data base provided by the USGS and the National Oceanographic and Atmospheric Administration (NOAA). From 10 to 300 km, we rely entirely on the USGS and NOAA data base, which contains measurements taken about every 700 m across the NTS.

In principle, if gravity were known all over the surface of the earth, we could make an exact prediction of gravity on the tower. Of course, practical considerations limit us to measuring gravity at only a finite number of locations. The number of locations and their spacing were chosen to minimize uncertainties in gravity predictions on the tower. Details of our error analysis and method for predicting gravity on the tower from ground gravity data are presented elsewhere.¹⁰

In addition to measuring the gravity at numerous locations on the surface and on the tower, we also had to determine the elevation at each of the measurement locations. For this purpose, we used an electronic distance-measuring device that emits an infrared pulse, which is reflected from a corner cube at a reference location. The round-trip time of the pulse, when corrected for atmospheric effects and earth curvature, allowed us to calculate the elevation to sufficient accuracy. We obtained elevation measurements on the tower at the same time as the gravity measurements, in case the tower were to expand or contract

with changes in temperature. We measured the elevation of the many surface gravity locations relative to the base of the tower, which was, in turn, measured relative to 10 surveyor's benchmarks located within 3 km of the tower.

Data Analysis

The first step in analyzing our gravity measurements was to remove from the data the gravitational effects of the moon and sun as well as the effect of the rotation of the earth (centrifugal force). We then used the surface gravity measurements to obtain predictions for gravity at the base of the tower and

Figure 2. Zero-length spring gravimeter, such as that used in LaCoste-Romberg gravity meters. A zero-length spring is prestressed so that a force is required to separate the coils. The spring supports a mass at the end of a beam. Thus, known relations of the spring force (product of the spring constant and the length of the spring), the length of the beam, the weight of the mass, and the angular displacement of the beam can be combined to determine the gravitational force.

Figure 3. Contour map of the BREN tower area showing locations of our surface gravity measurements. (There are 256 additional locations in the central region, which are not shown.) The triangles represent locations used in the first phase of the experiment; the locations marked with a plus are being used in the second phase; squares denote locations at which data were taken by the USCS or NOAA.

at each of the 12 tower platforms (at elevation z relative to the tower base). For the sake of comparison, we obtained the tower gravity predictions using two different approaches.

We obtained the first prediction, $g_{\text{cont}}(z)$, from ground gravity measurements using the method of "upward continuation of the surface gravity field."¹¹ We obtained the second prediction, $g_{\text{model}}(z)$, using a model of the earth that is azimuthally symmetric (i.e., having only radial density variations). We then formed the quantities $\Delta g_{\text{cont}}(z) = g_{\text{cont}}(z) - g_{\text{model}}(z)$ and $\Delta g_{\text{meas}}(z) = g_{\text{meas}}(z) - g_{\text{model}}(z)$. Thus, at each elevation z , we subtracted the same earth model prediction from the tower measurements and from the prediction obtained with the ground measurements. If the azimuthally symmetric earth model were correct at the BREN tower, then we would obtain $\Delta g_{\text{meas}}(z) = 0$ for all z .

Next, we plotted the residual gravity value between each tower platform and the lowest tower platform when the expected difference using the symmetric-earth model was subtracted. That is, we plotted $\Delta g_{\text{cont}}(z) - \Delta g_{\text{cont}}(0)$ and $\Delta g_{\text{meas}}(z) - \Delta g_{\text{meas}}(0)$ for each of the 12 locations on the tower as a function of z . Figure 4 shows the results, where circles denote gravity measurements and triangles denote predictions. Consider first the circles connected by the black curve in this figure. If the symmetric-earth model is accurate and if gravity is Newtonian, then this curve must be a straight line of constant zero value. Since it is not, we must conclude that either gravity is non-Newtonian or the earth model is wrong or both. This is the ambiguity that arises in borehole experiments.

The advantage of tower experiments becomes clear when we remove the ambiguity by using the surface gravity data. The blue curve in Fig. 4, which was derived from the surface measurements, falls almost directly on top of the black curve. We can compare these two curves directly because the same symmetric-earth model predictions were subtracted from each of them. The two curves are in excellent agreement, showing that, within the sensitivity of our experiment, gravity does indeed obey a Newtonian inverse-square law.

In addition, our data suggest that the azimuthally symmetric-earth model is not accurate enough to predict gravity at the BREN tower. Similarly, other experiments that rely solely on a symmetric-earth

model in their test for non-Newtonian gravity could encounter problems predicting gravity in other localities.

Conclusion

The results from the first phase of our experiment support Newton's theory of the gravitational force.¹¹ We observed no evidence for a fifth force to a sensitivity level of 1 part in 10^7 . This is the first tower experiment to observe a null result at this high level of sensitivity. In the second phase of our work, the sensitivity will be three times greater. Our results to date set strong limits on the strength and radial dependence of any possible fifth force and, thus, provide an important benchmark for grand unification theories.

Figure 4. Results of the first phase of our experiment. Tower-gravity measurements are well described by the predictions obtained from surface-gravity measurements. Any deviation from Newton's law of gravity would cause a discrepancy between the curves. Since the discrepancy between the two curves is smaller than the experimental uncertainty, our results support Newton's theory of the gravitational force.

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Grazing-Incidence Cherenkov X-Ray Generation

M. J. Moran

Laboratory x-ray sources are used for purposes that vary from industrial applications to studies on details of the interaction between x rays and matter. The type of x-ray source that is best for a given application often is determined by a variety of practical considerations. X-ray sources that derive their energy from a relativistic electron beam often are advantageous because the x-ray beams that they produce may have well-defined tunable energies, are highly collimated, have high spectral intensity, and may have useful degrees of spatial or temporal coherence.

Over a long history of experiments at the LLNL linear accelerator (linac), we have studied the generation of x rays with relativistic electron beams by a variety of mechanisms. One extended series of experiments concerned the generation of hard x rays by electrons channeling through thin, single-crystal wafers. In this context, "channeling" radiation results from a fundamentally quantum interaction between the relativistic electrons and the crystalline atomic potentials. These studies helped

stimulate a wide range of research efforts that focused on both the properties of crystalline materials and the generation of hard x rays with relativistic electron beams.

Another series of experiments focused on transition radiation in the soft x-ray spectral region that was generated when relativistic electrons passed through thin-foil targets. These experiments demonstrated that the longitudinal coherence of x rays could be used to design an x-ray source that produced an x-ray beam with high spectral intensity and whose photon energy could be "tuned" by choosing the angle of emission.

In more recent experiments, we have studied the characteristics of Cherenkov x rays. Both the Cherenkov x rays and their emission distributions are unusual in ways that might lead to future applications. The x rays are unusual because the Cherenkov effect generally is not possible for x rays. Recall that the Cherenkov effect occurs when an electron passes through an optical medium with a speed greater than the phase velocity of light in that medium, c/n , where c is the

speed of light in vacuum and n is the refractive index. Most x rays with frequency ω have a refractive index $n(\omega) < 1$ and a phase velocity greater than c . Cherenkov radiation is not possible in this case because electrons cannot have a speed greater than c . However, Cherenkov x rays are possible in some materials for x rays with frequencies near characteristic resonances in the material of interest. In these cases, $n(\omega)$ can vary rapidly [i.e., anomalous dispersion of $n(\omega)$] over narrow spectral bands, with the result that $n(\omega) > 1$ for some narrow range of frequencies. If this happens, then x rays can be generated by the Cherenkov effect.

Cherenkov x rays are of current interest for two main reasons. First, because their production is intimately related to anomalous dispersion of x-ray refractive indexes, they may serve as a useful tool for studying anomalous x-ray properties of materials. A better knowledge of anomalous x-ray refractive indexes, which have been extremely difficult to study with other techniques, might eventually prove useful in the design of x-ray optical

components. Second, the spectral and angular distributions of Cherenkov x rays are unusual in ways that might enhance their usefulness as a high-intensity, narrow-band laboratory x-ray source. This article describes some of these unusual features and our preliminary experimental results.

Theory and Modeling

When a particle with speed $\beta = v/c$ passes through a medium with refractive index $n(\omega)$, Cherenkov radiation will be emitted into a hollow conical distribution at the Cherenkov angle θ_c given by:

$$\theta_c(\omega) = \cos^{-1} \left[\frac{1}{\beta n(\omega)} \right]. \quad (1)$$

For x rays where $|n(\omega)| \approx 1$, and for relativistic speeds where $|\beta| \approx 1$, this equation reduces to:

$$\theta_c(\omega) \approx \cos^{-1} \left[\chi'(\omega) - 1/\gamma^2 \right], \quad (2)$$

where β has been replaced by γ through the relation $\beta = (1 - 1/\gamma^2)^{1/2}$, and $n(\omega)$ has been replaced by the real part of the susceptibility $\chi(\omega)$ through the relation $n(\omega) = 1 - \chi'(\omega)/2$. When $\chi'(\omega) \gg 1/\gamma^2$ (usually satisfied in our experiments), then Eq. (2) reduces to:

$$\theta_c(\omega) \approx \cos^{-1} \left[\chi'(\omega) \right]. \quad (3)$$

This result shows how the Cherenkov angle $\theta_c(\omega)$ is related to the susceptibility in the material of interest. Thus, measurements of the frequency-dependent x-ray Cherenkov angles $\theta_c(\omega)$ can be used to study anomalous x-ray refractive indexes through the function $\chi'(\omega)$.

Cherenkov x-ray spectra will consist of narrow bands near characteristic resonances in the material of interest. Furthermore, these narrow bands will tend to have frequencies just below the characteristic absorption edges in these materials. This means that Cherenkov x rays will have frequencies that allow them to penetrate relatively efficiently through the Cherenkov material. Thus, for example, Cherenkov x rays from a carbon sample would be ideal for x-ray investigations of carbon-containing materials.

Of course, the application of Cherenkov x rays to various problems also will depend on their intensity and angular distribution. Even though Cherenkov x rays have optimal transmission through their parent material, the ultimate intensity obtainable from a Cherenkov x-ray source will still be limited by absorption in the emitting target itself (Fig. 1). Using carbon as an example once again, targets thicker than a few micrometers (10^{-4} cm) will not show appreciable increases

of emission intensity as the target thickness increases because x rays emitted near the entrance surface will be absorbed before they can be emitted from the exit surface. The emission of Cherenkov x rays can be described by the formula:

$$N_c \approx 2\pi\alpha \left(\frac{l}{\lambda} \right) \left(\frac{\Delta\omega}{\omega} \right) \chi'(\omega), \quad (4)$$

where N_c is the number of photons emitted when an electron passes through a thickness l (taken to equal the x-ray absorption length) of material; λ_c is the Cherenkov wavelength ($\lambda = 2\pi c/\omega$); and $\Delta\omega$ is the bandwidth over which a given value of $\chi'(\omega)$ is valid. Equation (4) also assumes again that $\chi'(\omega) \gg 1/\gamma^2$. Typical values for these parameters lead to an N_c from 10^{-2} to 10^{-4} photons/electron.

However, detailed computer calculations of Cherenkov x-ray emission distributions have demonstrated a way around the limitation described above. The calculations showed that, if electrons are incident

Figure 1. Generation of Cherenkov radiation in absorbing media. The basic Cherenkov radiation geometry is maintained, but only one absorption length can contribute to emission from the medium. This figure ignores any refraction of Cherenkov radiation at the exit boundary of the medium.

with near-grazing angles on thin foils of the Cherenkov medium, then the number of photons that are radiated can increase dramatically, and the conical angular distribution can collapse into a collimated "pencil-like" beam. These changes become stronger as the grazing angle decreases.

This unusual behavior can be understood by comparison with Cherenkov radiation generated when an electron passes parallel and near to, but outside, a Cherenkov medium. This process has been discussed by several authors in the literature, and it has been important for some devices that produce Cherenkov radiation in the microwave spectral region. In the present case, grazing incidence represents an almost-parallel condition, where most of the Cherenkov x rays are generated while the electrons travel close to, but outside, the x-ray Cherenkov medium. In this way, Cherenkov x rays can be generated over electron path lengths outside the medium that are long compared to the x-ray absorption length in the Cherenkov medium itself.¹

The collapse of the angular distribution is a more subtle effect that results from refraction of the x rays as they escape from the Cherenkov medium. For near-grazing angles of incidence, Cherenkov x rays will be emitted at angles near, but still outside, the critical angle for total internal reflection. As a result, x rays that escape will be refracted, giving final angles of emission that are nearly parallel to the surface of the Cherenkov medium. However, for this effect to work as predicted, the medium must have a surface quality that allows x-ray reflection and refraction. This is no easy task, but it has been demonstrated in various optical elements that have been produced with modern optical-processing techniques.

Experiments

We have studied Cherenkov x rays in a recent experiment at the LLNL linac (Fig. 2). The experiment used a movable proportional counter to measure the angular distributions of x rays emitted when 75-MeV electrons passed through thin (about 3- μm -thick),

free-standing silicon and carbon membranes. The membranes were mounted on a holder that allowed the angle of incidence with the electron beam to be varied to any desired value.

For perpendicular incidence (Fig. 3), the angular distribution was essentially identical to those associated with transition radiation (TR). Two previous attempts to measure Cherenkov x rays with this geometry had obtained similar results. TR has a characteristic conical angular distribution, with an on-axis minimum and peak intensity at an angle of emission of $1/\gamma$. These results show that TR dominates x-ray emission from thin foils for perpendicular incidence of electrons.

However, as the angle of incidence was decreased, both the silicon and carbon samples yielded additional emission peaks at an angle of 40 mrad (Fig. 3). These peaks appear to be Cherenkov x rays because their intensity was expected to increase dramatically as the angle of incidence approached near-grazing values. No other mechanism has been identified that could explain this behavior. Since the Cherenkov peaks have a spatial intensity that is comparable to the TR peaks, the Cherenkov spectral intensity is about 100 times greater than that for the TR. This is because the TR has a broad spectral bandwidth (hundreds of eV), whereas the Cherenkov emission has an inherently narrow bandwidth (a few eV or less) because of its relation with anomalous dispersion.

Conclusions

The data in Fig. 3 provide strong evidence of grazing-angle enhancement of Cherenkov x-ray emission. Although the Cherenkov x rays did not refract in the manner predicted

Figure 2. Schematic diagram of the experimental arrangement. After passing through a thin-foil target, electrons are deflected by a magnet into a beam dump, where the beam current is monitored. Cherenkov x rays continue through the magnet and are measured by a movable proportional counter.

by calculations, the discrepancy can be ascribed to the surface quality of the samples, which was too poor to allow either reflection or refraction at the sample surface. The Cherenkov emission intensities were nearly consistent with our expectation.

We have designed and assembled a follow-up experiment that features a position-sensitive proportional counter (PSPC) and a multilayer-mirror monochromator. The PSPC will eliminate the need to physically scan the detector through the angular distribution of x rays and will produce a smoother, higher-quality measurement. The monochromator will allow better identification of photon energy ($\Delta E/E \approx 7\%$). This work will represent the first measurement of Cherenkov x rays that includes simultaneous measurement of photon energy and angle of emission. Data of this type can be used to study details of anomalous dispersion in various materials. The data also can be used to identify quickly those systems for which practical application of Cherenkov x rays can become a reality.

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Figure 3. Angular distribution of x rays from a silicon membrane. (a) Perpendicular incidence results in an emission distribution that is dominated by transition radiation (TR) peaks appearing at ± 7 mrad. (b–d) As the grazing angle of incidence is decreased, extra Cherenkov radiation (CR) peaks appear at ± 40 mrad.

High-Gain Optical Cherenkov Detector

M. J. Moran

Nuclear-test diagnostics often impose requirements on detectors that are extremely difficult to satisfy. On the one hand, detectors must be rugged to survive with good reliability the rigors of the downhole-

emplacement operation and waiting period that follows. On the other hand, they must include a variety of technical characteristics that may be unusual and inherently difficult to meet to generate the desired data.

One detector that has satisfied demanding requirements in outstanding fashion throughout nearly the entire nuclear-test history has been the LLNL vacuum Compton diode (VCD). The VCD has served

as the backbone of our nuclear-test diagnostics. This device is a simple detector that measures the electron current scattered from a "converter" plate by the gamma rays being measured. This simple design has helped to produce a highly consistent set of data from numerous experiments over many years.

The radiation response characteristics of the VCD derive directly from its detection mechanism, Compton scattering. Thus, the VCD is sensitive to almost any gamma ray with energy above 0.2 MeV. Because the Compton scattering efficiency is relatively small (about 0.3%), the detector sensitivity is also rather low, about 3×10^{-22} C/gamma ray

Diagnostic techniques intended to complement the VCD often have attempted to increase the information content of data by generating signals that are proportional to gamma rays having energies in

known narrow spectral bands. Such experiments usually have involved measuring Compton electrons whose energies have been analyzed by a magnetic spectrometer. Because Compton electron energies depend directly on the initial gamma-ray energies, detectors that are arranged to measure only specific electron energies also measure only the corresponding gamma-ray energies. Compton spectrometers have been used in this way to study gamma rays with energies from 1 to 20 MeV.

The information content of data acquired from a Compton spectrometer depends on the detector used to measure the Compton electrons. In the past, silicon *p-i-n* diodes have been the detectors most often used with Compton spectrometers. These detectors have advantages with respect to their compact size and high gain ($G \approx 10^4$); however, they suffer from their time response

($\tau \approx$ a few nanoseconds) and limited dynamic range (about 100:1).

We have designed and tested a new type of optical Cherenkov detector that could complement *p-i-n* diodes for energy-resolved gamma-ray measurements. This detector consists of:

- An optical medium in which Cherenkov light is generated and reflected in the forward direction.
- A toroidal lens that further collimates the light.
- An optical detector (photodiode) that generates an electrical signal.

The detector has moderately high gain (about 75) and a fast time response (a fraction of a nanosecond, depending on the photodiode), but it is not as compact as the *p-i-n* diode. In this article, we describe the theory and performance of our new high-gain detector and discuss some possible applications.

Theory and Design

The Cherenkov effect radiates photons when an energetic electron passes through an optical medium with a speed greater than c/n , the speed of light in that medium, where c is the speed of light in vacuum and n is the refractive index of the medium. Cherenkov radiation is unusual because it is radiated into a hollow conical distribution having a half-angle θ_c (Fig. 1) given by:

$$\theta_c = \cos^{-1}(1/n\beta), \quad (1)$$

where β is the relativistic speed v/c , and v is the electron speed. Therefore, for many optically transparent materials (with $n \approx 1.5$) and for even mildly relativistic electrons (with energies greater than 0.5 MeV), Cherenkov light will be radiated at

Figure 1. Basic Cherenkov radiation geometry. Cherenkov radiation is generated as an electron moves through an optical medium. Photons are emitted into a hollow conical distribution and form a wavefront that moves with the electron.

about 45 deg to the direction of the electron. This distinctive angular distribution can be used to design detectors that collect Cherenkov light with high efficiency while simultaneously rejecting light radiated in random directions.

Our detector (Fig. 2) uses the Cherenkov medium, ultraviolet-grade Lucite, in a geometry that converts the initial conical distribution of Cherenkov light into a collimated forward-directed beam. This is accomplished by total internal reflection of the Cherenkov light into the forward direction (off the Cherenkov cone surface) and further collimation with a toroidal lens in the base of the cone. The beam then is reflected and focused onto a detector window located at a nearby off-axis point. In addition to selecting light on the Cherenkov cone, this design has the advantage of locating the actual detection device (a photodiode) at a position that is removed from the initial radiation flux and, thus, reduces background contributions to the signal. The key to this approach is using diamond-turning lathes to fabricate the unusual Cherenkov radiator geometry with the high-quality optical surfaces that are required for total internal reflection and for the toroidal lens to function efficiently. The off-axis parabolic mirror is also somewhat unusual, but it is available as a standard off-the-shelf optical component. Ultraviolet-grade Lucite is advantageous as the Cherenkov medium because it is transparent over a broad range of wavelengths in the visible region, it is fairly convenient for diamond-turning fabrication, it is inexpensive, and its low atomic mass helps minimize the effects of electron scattering.

The design approach for the detector relied on computer ray tracing to choose an optical system that would efficiently collect and focus the Cherenkov light onto the photocathode of a photodiode (PD). The calculations, which were performed by M. Grazer at EG&G, Pleasanton, California, included estimates of the effects of transverse scattering of electrons as they propagate through the Cherenkov medium. This scattering has the effect of broadening the angular distribution of Cherenkov light, making it more difficult to collect the Cherenkov light efficiently. Computer modeling made it possible to optimize the overall radiator geometry, especially the parameters of the toroidal lens. The calculations included the parabolic mirror and led to a prediction of an approximately 0.3-in. focal diameter at the detector photocathode.

The Cherenkov technique is feasible because the number of photons radiated by each electron can be quite large. The equation describing the number of radiated photons can be written as:

$$N_c = 2\pi\alpha \left(\frac{l}{\lambda} \right) \left(\frac{\Delta\omega}{\omega} \right) \times \sin^2\theta_c \approx 250 \text{ photons/cm}, \quad (2)$$

where α is the fine-structure constant ($\alpha \approx 1/137$), λ is the photon wavelength, $\omega = 2\pi c/\lambda$, and $\Delta\omega$ is the bandwidth of interest. In the estimate given in Eq. (2), λ is an optical photon ($\lambda = 0.45 \mu\text{m}$) and $\Delta\omega/\omega \approx 0.5$. Thus, even if we use a PD with 15% quantum efficiency to detect the photons, a Cherenkov detector having a few of centimeters of useful radiating pathlength can still have a net gain (signal electrons out of the PD vs electrons into the cone) of nearly 100.

Figure 2. Cherenkov-detector optical system. Cherenkov light is generated as electrons travel from left to right near the axis of the truncated cone. This light is totally internally reflected toward the forward direction by the conical surface. A toroidal lens further collimates the light so that the off-axis parabolic mirror can reflect the light to a relatively small spot on the focal plane.

Figure 3. Components of the prototype Cherenkov detector. The final assembly has an overall length of about 7 in. The arm on the side can accommodate several types of photodetectors.

Experiment

A prototype detector (Fig. 3) was fabricated and tested in an experiment at the EG&G Santa Barbara Office (SBO) linear accelerator. The experiment measured the overall detector gain with two different PDs and used a television monitor to measure the diameter of the off-axis Cherenkov focal spot. For a PD having a 1.5-in. photocathode, the measured detector gain was 75 ± 7 , with a PD-limited full-width-at-half-maximum time response of 0.45 ns. For a PD having a 0.375-in. photocathode, the gain was reduced, but the time response (still PD-limited) improved to a full width at half maximum of 0.15 ns. Measurements with the television monitor showed that the focal-spot diameter was about 0.5 in. These results are in good agreement with our estimates. It is not surprising that the measured focal-spot diameter is somewhat larger than that predicted, since the spot diameter depends strongly on effects of electron scattering, which themselves are difficult to predict or describe accurately.

Applications

Applications of our detector probably will relate to low- to medium-resolution (± 10 to $\pm 50\%$) gamma-ray spectral measurements requiring medium sensitivity, high bandwidth, and large dynamic range. Measurements of this type have been used in the past to assess emission at a particular gamma-ray energy in the presence of large broadband backgrounds. Such measurements also may come to be used to obtain correlations with x-rays or other types of emissions during a nuclear explosion.

Electron-Beam Ion Trap

C. L. Bennett, P. Beiersdorfer, N. K. Del Grande, J. R. Henderson,
D. A. Knapp, R. E. Marrs, and M. B. Schneider

During FY 1989, we used the electron-beam ion trap (EBIT) to measure a variety of atomic physics quantities that have never before been measurable in laboratory experiments. Here, we describe some of the measurements of highly charged ions we made in EBIT, including measurements of high-resolution spectra and of radiative recombination (RR), dielectronic recombination (DR), resonant excitation (RE), and impact excitation (IE) cross sections. Because the highly charged ions that can be studied experience important relativistic and quantum electromagnetic effects, EBIT advances our understanding of the atomic physics properties of those ions and of the high-temperature plasmas in which highly charged ions are abundant.

The trapping region in EBIT (see Fig. 1) is formed by the combination of a strong axial magnetic field and an electrostatic well. The 3-T magnetic field squeezes a 0.2-A electron beam to a radius of 35 μm , which radially confines positive ions by the electron space charge. The electrostatic well confines the ions in the vertical direction to a region of about 2 cm. EBIT is described in detail in Refs. 1–5.

Currently, the energy of the electron beam in EBIT can be varied from 0.7 to 25 keV. This range enables the production of fully stripped ions with charges up to +42, of helium-like ions with

charges up to +80, and of neon-like ions of any element in the periodic table. Among the milestones we achieved during FY 1989 were the production of neon-like uranium

and the preliminary observation of its x-ray spectrum. We also moved ahead in the design of a Super-EBIT capable of producing bare ions of any element in the periodic table.

Figure 1. Schematic of the trapping region in EBIT.

Dielectronic Recombination Experiments

DR is a process of resonant recombination that is important in determining the charge-state distribution in plasmas. Measurements of DR that were begun last year were completed in some systems⁶ and continued and extended in others. One of the great difficulties in DR measurements is that the very large resonant DR cross sections

cause the target ion species to be destroyed as it is being measured. This problem may be overcome by a rapid switching of the electron energy between the resonant energy and a higher nonresonant energy, which restores the ionization balance of the charge state of interest. The lower electron energy (DR energy) is varied through the resonance region in successive runs, a tedious and difficult procedure

because it requires that consistent systematic conditions be maintained from run to run.

In FY 1989, we developed a new technique that greatly improves the quality of data obtained in DR experiments. In this method, we vary the electron-beam energy in a specific periodic pattern that ramps the beam energy quickly through the energies corresponding to DR resonances, while the largest fraction of the time is spent at a higher energy to preserve a high level of ionization. This ensures that the ionization balance is identical for every resonance as well as for the normalizing continuum RR. For each event, we record the electron-beam energy, the precise time within the voltage cycle, and the observed x-ray energy.

Scatter plots of the number of events vs electron-beam energy and observed x-ray energy exhibit interesting structure. Figure 2 is a scatter plot for gold ions showing peaks that arise from DR resonances; vertical ridges correspond to line radiation, and diagonal ridges correspond to the continuum RR. A DR peak occurs whenever an RR energy (on the diagonal) matches a line energy (on the vertical). Using this event-by-event technique, we can obtain data of much higher quality than ever before.

High-Resolution X-Ray Spectroscopy

We have undertaken extensive investigations of the $\Delta n = 0$ and $\Delta n = 1$ x-ray spectra of highly charged helium-like and neon-like ions. We demonstrated the possibility of making precise wavelength measurements, and we conducted detailed studies of various line excitation mechanisms, including electron IE, radiative cascades, inner-shell ionization, and recombination

Figure 2. (a) Scatter plot of event-by-event data for gold; (b) same data in a three-dimensional representation, in which the height of the peaks is proportional to the number of events.

feeding. High-resolution x-ray spectroscopy also provided information on the performance of the electron trap. Many of these measurements were made possible by improvements in EBIT's flat-crystal spectrometer and by the development of a new high-throughput, high-resolution von Hámós-type crystal spectrometer and a high-vacuum-compatible, low-energy spectrometer.

In FY 1989, we demonstrated the utility of the EBIT technique for precision wavelength measurements. A spectrum of the $n = 3 \rightarrow 2$ transitions in Yb^{60+} (obtained with EBIT's flat-crystal spectrometer) is shown in Fig. 3. The dominant features result from 2p-3d electric dipole transitions in neon-like ytterbium. The lines are labeled 3C and 3D in the notation of Loulergue and Nüssbaumer.⁷ The spectrum also shows the transition labeled 3F, as well as various unmarked satellite lines due to transitions in lower charge states. The line labeled 3A is a 2s-3p resonance transition. We can infer the self-energy contribution affecting 2s electrons from a precise measurement of the transition energy of line 3A because (unlike other transitions) line 3A involves a 2s core level and is, therefore, strongly affected by quantum electrodynamics (QED). Figure 3 also shows an electric quadrupole transition (line E2S) that has been of interest in high-density plasma research because of its density sensitivity.⁸ Line E2S is also strongly influenced by QED, but its intensity is weaker than that of line 3A, making it less useful.

To determine the transition energy of line 3A with highest precision, we measured the line with the new von Hámós-type crystal spectrometer. A spectrum of line 3A observed with that spectrometer is presented in Fig. 4a. The $\text{Ly}_{\alpha 1}$ and

$\text{Ly}_{\alpha 2}$ lines of hydrogenic zinc are used as calibration references. Figure 4b shows the location of the Ly_{α} lines with respect to line 3A. The wavelengths of the hydrogenic lines are very close to those of the neon-like line; hence, errors due to uncertainties in the dispersion of the spectrometer are small. The value of the self-energy contribution determined in this fashion is 18.37 ± 0.80 eV, which is 1.9 eV larger than predicted by standard multiconfiguration Dirac-Fock calculations.⁹⁻¹⁰

We also measured $n = 3 \rightarrow 3$ transitions in various high-Z ions, including platinum, gold, and mercury. Typical spectra for platinum and gold are compared in Fig. 5. The lines are labeled by the charge state, spin, and parity of the excited state whose decay to the ground state produces the measured x rays. The differences in amplitude for corresponding lines in the two spectra are the result of slightly different charge-state distributions, and the differences in relative position

Figure 3. Spectrum of $n = 2 \rightarrow 3$ transitions in neon-like ytterbium in the 0.125- to 0.155-nm wavelength region, obtained with a flat-crystal spectrometer. Unmarked features are transitions in lower charge states. Inset shows the spectrum of hydrogen-like and helium-like zinc used for calibration.

of the lines are the result of atomic interaction effects. The radiative corrections from QED to the 3s energy level are especially important in the $n = 3$ shell. Sodium measurements in particular provide the most reliable test of the QED radiative corrections for the $n = 3$ levels. Our most precise measurement to date is for the sodium-like transition in platinum, which happens to lie within 0.15 eV of a

transition in hydrogenic oxygen. For this case, we found the energy of the $3p_{3/2}-3s_{1/2}$ transition to be 653.44 ± 0.05 eV.

In FY 1990, we intend to improve the instrumentation so we can simultaneously acquire event-by-event DR data and high-resolution x-ray spectra. With this capability, we hope not only to be able to measure the dielectronic cross sections of individual resonances within the

$n = 2 \rightarrow 1$, $n = 3 \rightarrow 2$, and $n = 4 \rightarrow 3$ but also to observe spectra of very weak lines, such as $n = 3 \rightarrow 3$ neon-like transitions.

X-Ray Polarization Measurements

We have used EBIT to make the first measurements of the polarization of x rays from highly ionized helium-like and neon-like ions. It is not possible to make these

Figure 4. Spectra of some of the lines shown in Fig. 3—(a) in Zn^{29+} and (b) in Yb^{60+} —obtained with the von Håmos spectrometer. Differences illustrate the higher resolution and improved signal-to-noise ratio over the spectra obtained with the flat-crystal spectrometer.

Figure 5. Comparison of spectra of $n = 3 \rightarrow 3$ transitions in (a) platinum and (b) gold. The lines are labeled by charge state, spin, and parity of the excited state.

measurements on an isotropic source such as a plasma. However, in EBIT, the ions are nearly stationary, and the electrons have a well-defined impact direction, so there is no spatial averaging of the polarization of the resulting x rays.

We have used three techniques for measuring x-ray polarization, the most direct of which uses a Bragg diffraction crystal in a spectrometer to resolve the x rays of interest. We exploit a property of diffraction crystals where, with a Bragg angle near 45 deg, Bragg reflection occurs only for x rays with a polarization parallel to the surface of the crystal; the perpendicular component is absorbed. By making an initial measurement, rotating the spectrometer about its axis to EBIT by 90 deg, and making another measurement, we measure each component of the polarization of an x ray separately and, thus, determine the polarization. Figure 6, which shows a comparison of scandium spectra taken in the two orientations, illustrates a typical result of this process. The differences in the spectra are the result of different polarizations for the various lines.

The main result of our measurements was the observation of the unexpectedly large effect on the polarization of the hyperfine interaction. The measurements we made for helium-like scandium¹¹ were completely incompatible with previous calculations for the polarization that did not account for hyperfine interaction. Subsequent calculations including the hyperfine interaction do agree with our data; our results for helium-like iron,¹² which will not have the hyperfine interaction, are also consistent with calculations. Similarly, preliminary results for neon-like barium agree with calculations.

Figure 6. The strengths of lines *w*, *x*, and *y* for helium-like scandium excited by 4.36-keV electrons, shown in the (a) parallel orientation and (b) perpendicular orientation.

Figure 7. (a) Spectral measurement of uranium excited by 7.5-keV electrons compared with (b) a calculation for nickel-like uranium using the HULLAC code.

Nickel-Like Uranium

We have also measured higher-shell spectra from near nickel-like uranium. A comparison of the spectra measured with a windowless Si(Li) detector and spectra calculated by Osterheld (private communication, 1989) shows excellent qualitative agreement (see Fig. 7). Of particular interest are the manifold of $4 \rightarrow 3$ transitions dominated by a strong electric quadrupole $4s-3d$ transition, which is about as large as the leading dipole $4f-3d$ transition. It is also important to note the electric quadrupole $4f-3p$ transition bracketing the high-energy side (below 4.5 keV) of the $4 \rightarrow 3$ transitions. These spectral features are associated with cascading for nickel-like ions, which have 28 electrons in a closed $3d^{10}$ configuration.

We plan to use a crystal spectrometer to study details of fine structure with much better resolution. To determine the ionization cross sections of specific highly stripped ions, we need a far more precise determination than is currently possible of the individual charge-state abundance at a given bombarding energy.

Extracted Ion Experiments

Highly charged argon and xenon ions produced through electron impact ionization and excitation in EBIT have been efficiently extracted from the trap and have been mass and charge analyzed by the Ion Collision Group. From these analyses, members of the group have deduced relative yields for the production of argon ions with charge states up to +17 and xenon ions with charge states up to +44. The emission of ArK x rays following Ar^{17+} ion impact on a copper surface has

been observed, demonstrating electron capture into high- n states.

A typical extracted charge-state spectrum for xenon ions is shown in Fig. 8.

With EBIT, we have obtained precise measurements of properties of highly charged ions that have never before been attainable. These measurements include high-resolution spectra, IE cross sections, and various resonant processes.

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Figure 8. Extracted charge-state spectra for xenon plus contaminants, produced with electron energies of (a) 8 keV and (b) 3 keV.

Optimal Configuration of Optics for Collimating Amplified Spontaneous Emission

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With the demonstration of the soft x-ray laser¹ in 1984, interest in understanding the propagative aspects and spatial-coherence characteristics of amplified spontaneous emission (ASE) sources² has been renewed. Driving this renewed interest is the fact that x-ray lasers are not conventional lasers in which propagation and coherence depend strongly on cavity (oscillator) design. At present, no cavities exist for x-ray lasers, although ideas are being actively pursued.³ The lack of usable cavity designs derives from two basic difficulties in the production of x-ray lasers. The first difficulty concerns the necessity for long cavity lengths, associated with low gains and harsh environments, coupled with the short lifetimes of the

laser-produced plasmas, which act as the amplifying medium. The second difficulty relates to the immaturity of x-ray optical technology. Because of these shortcomings, x-ray lasers are simply quantum-noise amplifiers. The spatial characteristics of the output radiation of such sources result solely from the traveling-wave-propagation characteristics of the amplifying medium and do not rely on the evolution of coherence associated with the buildup of standing waves in a laser oscillator. This article describes our recent modeling efforts and experiments to determine where to locate the focal point of a collective optic along the longitudinal axis of an amplifier to optimally collimate the output radiation of an ASE source.

Simple Model

The use of output radiation from an x-ray laser depends on how well we can control the emergent beam from an ASE source. Control of such a beam means reducing the divergence either by collimating or focusing the beam. Perfect collimation of an ASE source is unobtainable. We may seek to collimate the light from a luminous disk with source diameter s by placing a lens of focal length f at a distance of one focal length from the source (Fig. 1a). The beam after the lens then has a divergence of s/f [full width at half maximum (FWHM) in radians]. Perfect collimation is, therefore, only possible for a point source with an infinitesimally small size. These results are well-known from geometrical optics.⁴

An ASE source, however, is not so simple. Not only does an ASE source have transverse dimensions, but the longitudinal dimensions must also be considered. Along the longitudinal direction, we must consider the distribution of sources (spontaneous emission) and the distribution of gain (amplification). In this discussion, we consider only the geometrical aspects. A luminous disk that has its emanating rays constrained by a tube-like structure can be analyzed according to Fig. 1b. Consider the distribution of rays in one transverse dimension inside the tube (amplifier) as a function of longitudinal position. At either end of the tube, the distribution has a square shape with an angular distribution (θ) of s/f . At the center of the tube, the

Figure 1.

(a) Simple model for collimating light from a luminous disk with source diameter s . For a lens with focal length f located one focal length from the source, the beam has a divergence of s/f (FWHM). (b) Improved analysis for a luminous disk with emanating rays constrained by a tube-like structure.

transverse distribution is peaked and falls off monotonically to zero at the ends of the distribution with an angular distribution θ of $s/2f$. Between the center and the ends of the amplifier (in the longitudinal dimension), the distribution changes smoothly from a triangular to square shape. Rounding of the shape of the distribution occurs in the intermediate region.

To optimally collimate the radiation emanating from such a structure, we must determine where to place the focal point of a lens along the longitudinal dimension to deliver the maximum amplitude in a package of minimum size. This determination involves mapping the transverse distribution of rays with a lens from a given longitudinal position inside the tube to an infinite distance after the lens. The package size corresponds to the shape of the distribution of rays, and the amplitude corresponds to the density of the distribution of rays.

Experiment

To determine how this simple model relates to a real ASE source, we conducted the imaging experiment shown in Fig. 2. We studied the ASE sources that are created when population inversions (gain) are produced in small-aspect-ratio dye samples. We used dye-laser ASE systems as analogs of x-ray lasers.⁵ We selected Rhodamine 6G dyes (R6G) because high gains and, therefore, saturated systems can be produced. Saturation is achieved when the growth of the ASE intensities changes from exponential to linear. It is important to be able to reach the saturated regime to see whether saturation affects the propagative aspects of the ASE source.

The dye samples were pumped with the second-harmonic output of a Q-switched Nd:YAG laser (pulsewidth = 10 ns, $\lambda = 532$ nm). The pump is expanded, and a uniform portion of the beam is passed through a variable slit (dimension h). The illuminated slit is relay-imaged (in the h dimension) onto the dye cell using a cylindrical lens placed one focal distance from the slit. Relay imaging the illuminated hard aperture of the slit onto the dye cell overcomes the problem of diffraction through the slit. This technique provided a uniform pump beam in the h dimension. The pump radiation impinges on the side of a flowing dye cell containing R6G dissolved in dimethylsulfoxide ($1.8 \times 10^{17} \text{ cm}^{-3}$). Transverse pumping of the dye cell creates counterpropagating ASE waves. The pump intensity

could be varied to create systems that have no amplification (fluorescence), exponential amplification (unsaturated gain), and linear amplification (saturated gain). The dimensions of our ASE system were 0.275 mm high $\times$ 0.60 mm deep $\times$ 18.0 mm long.

The output radiation of the ASE source was imaged by a lens-camera system mounted on a translation stage. The translation stage was arranged so the focal point of the lens could be placed at any position along the longitudinal axis L of the amplifier. The lens axis was aligned (centered) along the propagation axis of the ASE radiation. The lens of the imaging system had a focal length of 75 mm, and the camera was located 200 mm from the lens. By using the simple lens formula,⁴ the effective focal length of the lens

Figure 2. Imaging experiment to determine how a simple model relates to a real ASE source. The R6G dye samples were pumped with the second-harmonic output of a Q-switched Nd:YAG laser. Transverse pumping of the dye cell creates counterpropagating ASE waves. This ASE system is 0.275 mm high $\times$ 0.60 mm deep $\times$ 18.0 mm long. Output radiation of the ASE source was imaged by a lens-camera system mounted on a translation stage arranged so the focal point of the lens could be placed at any position along the longitudinal axis L of the amplifier.

was 103 mm, and the magnification of the image on the detector plane (camera) was 2.67.

Deconvolving the magnification factor with the aid of a computer yielded an experimental setup in which the camera was effectively at an infinite distance from the lens. Although the setup shown in Fig. 2 assumes the appearance of a collimation experiment, it is, in reality, an imaging experiment. In fact, we were mapping the angular distribution of the radiation onto a positional distribution on the detector. By translating the lens, we could interrogate the angular distribution of radiation as a function of longitudinal position of the amplifier. The camera was a charge-injected-device (CID), solid-state television camera, and images were digitized and stored on a personal computer for further analysis.

Results

We used the amplitude and divergence of the intensity profile to determine where to place the focal point of a lens along the longitudinal axis of the amplifier for optimum collimation of output radiation. The point at which the amplitude is maximum and the divergence is minimum corresponds to a lens configuration that delivers maximum fluence of radiation downline from the lens. The results of such an experiment are shown in Fig. 3. On the basis of our criteria, it is obvious that the focal point of the lens should be placed at the center (longitudinally) of the amplifier. Here, we analyze only the intensity distribution in the h dimension. The ASE source under consideration was fully saturated (high gain). We found similar results in systems with lower gain

as long as gain (amplification) was present. The results were significantly different if no gain (fluorescent system) was present.

The energy propagating through the lens is independent of where the lens is positioned. Therefore, the area under the profiles should be independent of lens positioning. The results of Fig. 3 are in good agreement with the concept of energy conservation. The maximum amplitude is approximately four times the minimum amplitude measured, and the minimum divergence is approximately two times the maximum divergence measured. The discrepancy, a factor of 2 in terms of energy measured, results because we only analyzed one dimension of the intensity distribution. This discrepancy is resolved by assuming that the lens acts similarly in the other dimension (spherical lens).

Although recognizing that energy conservation is obeyed demonstrates that our experimental results are qualitatively correct, we have not proven that our simple model is sufficient to describe what occurs inside the amplifier. To prove our simple model, we must look at the actual shapes of the intensity profiles measured in the experiment. Figure 4 shows the intensity profiles measured for three focal-point positions of the lens. When the focal point of the lens is placed at the front (green) of the amplifier, we observe a flat-topped distribution. Placing the focal point one-quarter of the way into the amplifier produces a rounded distribution (blue). Placing the focal point at the center of the amplifier (optimum collimation) yields a triangular distribution (red). The results quantitatively prove our

Figure 3. Results of the experiment shown in Fig. 2. Energy propagating through the lens is independent of where the lens is located; therefore, the area under the profiles should be independent of lens positioning. The results shown in this figure are in good agreement with the concept of energy conservation.

simple model. Not only is energy conservation obeyed, but also the shapes of the profiles and their angular distributions θ are exactly what is predicted. The angular distribution of radiation emitted from an ASE source with a transverse dimension h of 0.275 mm that is imaged with a lens of focal length 103 mm should be 2.67 and 1.34 mrad if the focal point of the lens is positioned at the front (s/f) and middle ($s/2f$) of the amplifier, respectively. Within experimental error, we have quantitative agreement with these calculations.

To further prove our simple model, we conducted the experiment suggested by Fig. 1b. We replaced the ASE source in Fig. 2

with a luminous disk (light bulb with diffuser) whose light rays were constricted by two apertures with diameters of 3.6 mm and separated by 45 mm. The two apertures in optical series acted as the tube-like structure in the simple model. Figure 5 shows the results of the imaging experiment conducted on this substitute source. The intensity profiles are qualitatively similar to those measured on the ASE source. The divergences are within the experimental error of those predicted from the simple model. Again, we see the trend in the intensity profile progressing from square to triangular as the focal point of the lens is translated from the front to the middle of the source.

Modeling

The predictive quality of the simple model is astonishingly good, considering that it does not include the complexities of the ASE source. The complexities include gain amplification, saturation, and a distribution of spontaneous-emission sources throughout the amplifier. We have developed a computer code, Beam 3, that includes all of these complexities (G. Maenchen, Lawrence Livermore National Laboratory, private communication, 1989). Beam 3 is a three-dimensional, time-dependent, Monte Carlo ray-tracing code that includes the physics of light amplification in an active medium.

Figure 4. Measured intensity profiles for three focal-point positions of a lens. Placing the focal point at the front of the amplifier yields a flat-topped distribution (black). Placing the focal point one-quarter of the distance into the amplifier produces a rounded distribution (dark blue). Placing the focal point at the center of the amplifier (optimum collimation) yields a triangular distribution (light blue). These results quantitatively prove our simple model described in text.

Figure 5. Results of an imaging experiment in which the ASE source in Fig. 2 is replaced with a luminous disk (light bulb with diffuser) whose light rays were constricted by two apertures with diameters of 3.6 mm and separated by 45 mm. The two apertures in optical series act as the tube-like structure in the simple model. The intensity profiles are qualitatively similar to those measured on the ASE source, progressing from square to triangular as the focal point of the lens is translated from the front to the middle of the source.

Figure 6 shows the results from a Beam 3 calculation simulating our experimental results of Fig. 4. The only difference between the simulation and experiment is that the gain profile in the d dimension is assumed to be uniform in the simulation, whereas the gain profile in the d dimension falls off because of the attenuation (absorption) of the pump profile in the real ASE source. Even with this difference, agreement between experiment and simulation is excellent.

In work in progress, we are including the proper dependence of gain in the d dimension, which is directly proportional to the pump intensity at any given point. The functional form of pump-beam attenuation is quite

complex because of the dynamics of our four-level dyes.⁵ For a pump intensity below or above the absorption saturation intensity, the pump attenuation would normally be exponential or linear, respectively. However, because the ASE field is coupled to the pump field by the gain medium, the pump attenuation in our system is a function of longitudinal position of the amplifier. For an incoming pump intensity above the absorption saturation level, the pump will be linearly attenuated in the center of the amplifiers and exponentially attenuated at the ends. We are incorporating the phenomenon known as nonsaturable absorption due to stimulated emission of radiation into Beam 3.

Future Work

Our plans include studies of the spatial coherence of ASE sources. If we are to correctly control the propagation of output beams of sources with phase-sensitive lenses, or if we are to use ASE sources for holographic imaging (x-ray laser imaging of biological systems), then we must understand the phase relations between different parts of the beam. Issues that must be addressed include:

- Whether there are any correlations between different portions of a beam that originate from quantum-mechanically uncorrelated sources.
- How gain and saturation might affect these correlations.

Figure 6. Results from a Beam 3 computer-code calculation simulating the experimental results of Fig. 4. The gain profile in the d dimension is assumed to be uniform in the simulation, whereas the gain profile in the d dimension falls off because of attenuation (absorption) of the pump profile in the real ASE source. Even with this difference, agreement between experiment and simulation is excellent.

Figure 7. Intensity profiles measured in an imaging experiment in which a dye sample is pumped with low intensity, so that there is no gain. This source has the same geometry as our ASE source but does not amplify photons. The intensity distributions of the imaged outputs of the fluorescent source are strikingly different from those in which amplification is present.

- Whether a general theory can describe the transition between a quantum-mechanical (fluorescent) system to a classical (fully saturated ASE) system.

We believe these issues can be addressed by conducting Young's two-slit experiments on ASE sources as a function of gain of the systems. The imaging experiments already conducted point to interesting gain-dependent phenomena. Figure 7 shows intensity profiles measured in an imaging experiment that is the same as the one in Fig. 2, except the dye sample is pumped with an intensity low enough so that there is no gain. This source has the same geometry as our ASE source but does not amplify photons (simple fluorescence). The intensity distributions of the imaged outputs of the

fluorescent source are strikingly different from those in which amplification is present. We plan to study the physics of how propagation through a gainy medium provides cooperative behavior (or beam formation) of radiation originally emitted from individual quantum-mechanical sources.

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L-Shell XANES Experiment for 3d Transition Metals

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The L-shell x-ray absorption near-edge structure (XANES) for the solid 3d transition metals—calcium (20) through copper (29)—is dominated by atomic-like behavior that is poorly understood.¹ This behavior has been studied with electron energy-loss spectroscopy (EELS), a method that measures electrons to study x-ray processes, and with bremsstrahlung isochromat spectra (BIS).^{2,3} However, both of these methods provide relative rather than absolute cross sections, and neither is adequate to explain photoionization for solids. More and better

photoabsorption cross-section measurements are needed over the sparsely studied region between 400 and 1500 eV to test theoretical methodologies that fuse atomic and condensed-matter theories. We are reporting absolute photoabsorption cross sections taken during FY 1989 with the spherical grating monochromator on beamline 8-2 at the Stanford Synchrotron Radiation Laboratory (SSRL), in conjunction with earlier results taken on beamline 3-4 at SSRL and beamline U14A at the National Synchrotron Light Source (NSLS).⁴⁻⁶

Experiment

As part of the effort to characterize the filters, detectors, and optical elements used for Nevada Test Site diagnostics, we measured high-resolution (1-eV or better) near-edge, absolute photoabsorption cross sections in addition to broad-range photoionization cross sections for well-characterized carbon-only and carbon-metal multilayer targets (100 to 500 nm thick). Our absolute cross-section measurements were taken in transmission for titanium, chromium, iron, nickel, and copper with overall uncertainties of 10% or

Figure 1. Our photoabsorption cross-section measurements (with overall uncertainties of 10%) compared with the LLNL subkeV theoretical data bases^{8,10} for 3d solid metals: (a) titanium, (b) chromium, (c) iron, (d) nickel, and (e) copper. Experimental data from Ref. 9 (with 3% uncertainties) were used to normalize our data for iron.

less, a significant improvement over existing measurements, which have uncertainties five or ten times larger. The broad-range cross sections were determined with relatively thick targets; away from edges, targets had photon penetration depths of one-third to three mean free paths, enabling us to reduce statistical fluctuations to less than 2%. In Fig. 1, our cross sections are compared with theory and earlier results.⁷⁻¹⁰ We used targets that were thinner by a factor of 3 or 4 to resolve the close-in resonance structures shown in Fig. 2 (Ref. 7) because it would be difficult to make accurate cross-section measurements using only one target thickness at an edge where the resonance represents a change in the mean-free-path thickness of a factor of 10 or more.

Synchrotron radiation sources allowed continuous coverage across the oxygen K absorption edge at 543 eV, making evident the necessary corrections for oxide impurities. We determined the target metallic areal densities (mass per unit area) to better than $\pm 10\%$. Using accurate balances, ion back-scattering, and particle-induced x-ray emission, we characterized targets for their total as well as their component-element purity, weight per unit area, effective thickness (assuming normal density), and composition.

Discussion

As shown in Fig. 1, comparisons of our experimental results with single-particle Hartree-Slater (HS) theory^{8,10} agree for most 3d metals both below and at twice the energy of the ionization threshold. The dominant 2p-3d autoionizing resonances shown in Fig. 2, however, are associated with bound-bound transitions, which lead to nonradiative Auger decay. What is therefore measured is a combination

of the bound-bound photoabsorption and bound-free photoionization cross sections. Our results are of particular interest because they include these combined effects, whereas the available HS calculations for the atom do not include the bound-bound transition component for the atom or band theory to address the behavior of the solid.

As noted in Fig. 2, there is a buildup in the relative intensity of the $2p_{3/2}$ resonance compared to the $2p_{1/2}$ resonance at their respective L_3 and L_2 absorption edges. This buildup occurs as the 3d shell becomes filled. The 3d vacancies for titanium, chromium, iron, nickel, and copper are eight, six, four, two, and zero, respectively. The lighter,

Figure 2. Our measured XANES for (a) titanium, (b) vanadium, (c) chromium, (d) iron, (e) nickel, and (f) copper, showing the atomic-like 2p-3d autoionizing resonances that dominate the L_3 and L_2 edge structure.

low-atomic-number metals with more 3d vacancies have relative L_3 to L_2 resonance intensities significantly less than the standard assumption of a two-to-one ratio. Copper, having no 3d vacancies, has no 2p-3d autoionizing resonances. However, some (much smaller) 2p-4d autoionizing resonance structure is evident. Since the measured total cross sections have two major components (associated with bound-bound and bound-free transitions), calculation must be refined

to determine the relative contributions of these two components before true comparisons can be made with the measured photoabsorption cross sections. Our observations were that, within the experimental uncertainties, the oscillator strengths for the titanium relative to the nickel bound-bound transitions are about four to one. This is expected because titanium has eight vacancies, or four times as many vacancies as nickel, in its respective unfilled 3d subshells.

We found good qualitative agreement between L-shell XANES and atomic calculations for the 2p-3d bound-bound transitions performed by Mau Chen (Lawrence Livermore National Laboratory, private communication, 1989) that use a multiconfiguration Dirac-Fock (MCDF) model. Those calculations assumed a statistical distribution for the initial atomic states and were performed in intermediate coupling with configuration interactions. The calculations were folded with a resolution function to

Figure 3.

Our measurements dominated by L-shell (2p-3d) autoionizing resonances for titanium, vanadium, iron, and nickel (at right), showing qualitative agreement with MCDF-based calculations for the bound-bound transitions, assuming a statistical distribution of initial states (at left, after M. H. Chen, Lawrence Livermore National Laboratory, private communication, 1989).

simulate an experimental resolution of 0.3%. Our experimental results and MCDF-based calculations are compared for several representative solid 3d transition metals in Fig. 3.

It is not yet clear why results of atomic calculations that assume a statistical distribution of initial states should agree, on a relative scale, with the line shape of our measurements for solid titanium, vanadium, iron, and nickel, whereas those that assume the ground state do not. This agreement between theory and experiment suggests that, where comparisons can be made, the near-edge fine structure is basically atomic in nature and that the assumption of a statistical distribution of initial states must account

for some important property of the solid. More work is required before we can understand why atomic models explain near-threshold photoabsorption better than the present solid-state models. This understanding might be advanced by an approach that combines atomic and condensed-matter theoretical methodologies.

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Fission Time Studies via K-Vacancy Production in Deep-Inelastic Uranium + Curium Collisions

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As the reaction partners emerge from a deep-inelastic nuclear collision, they essentially retain their target-like and projectile-like identities and share the total kinetic energy damped in the process. If this energy is subsequently shared among the many nucleons of each partner, these partners can be considered compound nuclei with varying degrees of excitation energy. The decay of a compound nucleus has a unique signature independent of the specific de-excitation channel. We are attempting to measure the reaction product lifetime with respect to fission in order to learn about the fission process in these heavy excited nuclei, to see whether compound

nucleus theory is applicable to deep-inelastic reaction products, and to learn more about the inner-shell excitation process in high-Z atomic collisions.

In FY 1989, we completed an experiment that measured the inner-shell vacancy production in U + Cm collisions at a bombarding energy of 7.5 MeV/u. One objective of this work, discussed below, was to determine fission lifetimes via a technique that uses as a clock the correlations of molecular orbitals and atomic vacancies formed during the collision. Here, we report on the details and motivation of the experiment, but much analysis remains before a conclusion can be reached.

Molecular Orbital Formation

In very-high-atomic-number (high-Z) ion-atom collisions, where projectile energies exceed a few MeV/u, the inner-atomic orbitals of the collision partners adjust as they overlap to form dynamic molecular orbitals.¹ The collision energy is great enough to push the nuclear charge centers closer together than the atomic inner-shell diameter, but small enough so the projectile ion velocity is less than the inner-shell electron velocity. Under these conditions, quasi-molecular orbitals (MOs) can be formed. Because the internuclear separation changes at such close proximity, strongly varying electromagnetic fields cause electrons to be

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Figure 1. Schematic diagram of an ion-atom collision that undergoes a nuclear deep-inelastic reaction and, hence, experiences a time delay. The breakup mode following the nuclear interaction is two-body. Subsequent fission of the reaction products is not shown.

ejected into the continuum or to be excited to higher states. Vacancies in the MOs form as a result of these processes.² For very high- Z collisions, such as $U + Cm$, the MO is short-lived in comparison to the lifetime of the vacancy. After the collision, MO vacancies correlate to the inner shells of the atomic partners and decay as single-atom vacancies.²

If the projectile energy is large enough to overcome mutual Coulomb repulsion between the colliding high- Z nuclei to the point at which they interact, an exchange of nucleons and a damping of some collisional energy will occur.³ A composite system briefly forms where the nuclear force pulls the nuclei together and the Coulomb force pushes them apart. The nuclei essentially retain their individual identities and, sharing the damped energy, eventually break apart into target-like and projectile-like products of the reaction.⁴ Figure 1 shows each step of this process and the accompanying MO stages. When the orbitals change from single atom to united atom and back again, they create vacancies as shown in Fig. 1b and d. These vacancies transfer to the single-atom reaction products in Fig. 1e. If the reaction products can rid themselves of sufficient energy by nucleon or gamma-ray emission, they will remain intact, and the vacancies will decay like the x rays that are characteristic of the single atom after the collision. However, because the reaction products have experienced some exchange of mass and charge, are highly excited, and have a high Z , they may also undergo fission.^{5,6}

To understand the dramatic effect that fission can have on the atomic physics of these collisions, we must look at how the MOs correlate from the incoming to the outgoing system. Figure 2 shows

Figure 2. Complete molecular orbital correlation diagram for $U + U$ collisions and breakup. Vacancies can be created during stages b or d where the internuclear separation R is changing.

how the innermost orbital changes in $U + U$ collisions, where the a to e regions in Fig. 2 correspond to steps a to e in Fig. 1. As the internuclear separation decreases, the binding energy increases, and the $1s$ orbital splits into two MOs (the $1s\sigma$ and $2p\sigma$) on the incoming channel. If the exchange of charge and mass is insignificant, the two MOs converge back to the $1s$ orbital on the outgoing channel.⁷ For the brief time that the composite system exists between the incoming and outgoing MO stages, the system coalesces in the static configuration of an atom with the combined Z of the two collision partners (Figs. 1c and 2c). Because fission occurs after the composite system breaks apart, it only affects the outgoing channel, and this effect depends on the time needed for the excited reaction products to fission.

Effects of Fission

For fission to change the outgoing MO situation, it must occur before the correlation to single-atom orbitals is complete. Figure 3a shows the outgoing correlation for very late fission ($\geq 10^{-18}$ s), which has no effect on the molecular orbitals. However, at the other extreme, fission happens immediately after the nuclear composite system breaks apart ($\sim 10^{-20}$ s). In this case, only the innermost $1s\sigma$ MO correlates to the remaining intact reaction product, and the $2p\sigma$ MO now correlates to the fission fragments (Fig. 3b). Between these limits, the $1s\sigma$ and $2p\sigma$ MOs start to converge and approach a region in which vacancies can be shared⁸ (Fig. 3c). If fission happens near this region but still before single-atom orbitals are formed, consequences of the vacancy sharing would be apparent in the measured x-ray spectrum.

Figure 3. Outgoing correlation diagrams for three-body breakup ($U + U \rightarrow U' + 2Pd$) at extreme and intermediate fission times, T_f .⁹ (a) $T_f > 10^{-18}$ s, (b) $T_f \sim 10^{-20}$ s, and (c) 10^{-20} s $< T_f < 10^{-18}$ s. The shaded box in (c) is the region where vacancy sharing is likely to occur.

The $2p\sigma$ MO is less deeply bound than the $1s\sigma$; therefore, as a rule, it should always correlate to the exit channel with the lowest binding energy (in this case, that of the fission fragments). This MO situation should be similar for symmetric $U + U$ collisions and asymmetric $U + Cm$ collisions because the atomic numbers are so close. The only difference is that, for $U + Cm$, the final state x-ray energies are separable. Using these correlations to measure the atomic vacancy production in a high-Z, deep-inelastic, heavy-ion collision, we should be able to determine the fission lifetime of the reaction products. This technique was first described in Ref. 9 and has been applied to $U + U$ collisions at 7.5 MeV/u.

Experimentally, we measure the K-vacancy production probability (P_K), which is the number of particle-x-ray coincident events divided by the number of particle detector

efficiency and solid angle. Because the fission time depends on the degree of excitation of the reaction products, which in turn depends on the energy lost in the nuclear interaction, we measure P_K as a function of the total kinetic energy loss (TKEL) of the nuclear interaction,¹⁰ where the TKEL is simply the negative of the nuclear Q value for the reaction. To obtain a meaningful result, we must measure P_K for nonfissioning (two-body) and single fissioning (three-body) events. Figure 4 shows a measurement⁹ of the two-body P_K for $U + U$ collisions at 7.5 MeV/u compared with a calculation of the same.¹¹ The calculations in Fig. 4 use the quasi-molecular picture to describe inner-shell excitation with a time delay between the incoming and outgoing channels. They include multistep excitations (electron excitation by various intermediate states) and coupling between continuum states. The calculation is

done as a function of the delay time (nuclear interaction time), which can be related to the TKEL. Basically, the more energy damped in the composite system, the longer the system must exist. The reduction of P_K with time is known as the time-delay effect, and the influence of nuclear reaction times on atomic inner-shell vacancy production is well established.¹²⁻¹⁴

As the TKEL increases, the probability of fission increases. Therefore, a comparison of $P_K^{\text{two-body}}$ to $P_K^{\text{three-body}}$ could yield information on the fission dynamics. Figure 5 represents the time-delay effect for two- and three-body events. This model⁹ assumes that at small excitation energy, the fission time T_f (reaction-product lifetime after decay of the deep-inelastic composite) is longer than the decay time of K vacancies (T_K), which are created in the collision. As the reaction products

Figure 4. Atomic K-vacancy production probability for $U + U \rightarrow U' + U''$ at 7.5 MeV/u (from Ref. 9). (a) Measured P_K . (b) Calculated P_K (Ref. 11) normalized to the experimental TKEL = 0.

become more excited, the probability for faster fission increases. Hence, if T_f is a sensitive function of excitation energy that makes a transition from $>T_K$ to $<T_K$ in the measurable TKEL range, the three-body P_K will change. As T_f approaches T_K , vacancies correlating to the fissioning reaction partner no longer decay as uranium-like K x rays, so P_K is reduced. For $T_f \approx T_K$, the two inner MOs that contribute to the two-body P_K can share vacancies,⁸ and P_K is reduced to about one-half the two-body value (VS regime in Fig. 5). As T_f becomes much smaller than T_K , fission occurs before vacancy sharing can, and only the innermost 1σ MO purely contributes to P_K . Because most of the ionization results from the $2p\sigma$ MO,^{11,15} which now no longer contributes to the relevant x-ray yield, the three-body P_K is reduced to $\sim 10\%$ of the two-body P_K (see 1σ regime in Fig. 5).

Previous Results

In the U + U experiments,⁹ $P_{K, \text{two-body}}$ and $P_{K, \text{three-body}}$ agreed within experimental error for TKEL as large as ~ 175 MeV. When TKEL ≈ 175 MeV, the three-body data appeared to drop below the two-body data but not outside the error. A significant difference in P_K would mean T_f is shorter than T_K . We continued to measure TKEL up to 275 MeV. Because the two-body and three-body P_K still agreed, we concluded that T_f is always larger than T_K . The time scale of these measurements is based on the decay time¹⁶ of a K-shell vacancy, which is $\approx 10^{-10}/Z^4$, or 1.4×10^{-18} s for uranium. Anholt and Rasmussen¹⁷ used Dirac-Hartree-Fock wave functions to determine transition rates and lifetimes in high-Z atoms. They calculated the

uranium K-vacancy lifetime to be 5.2×10^{-18} s. Hence, the U + U data indicate that $T_f > 10^{-18}$ s for the entire measured range of TKEL. This result is interesting, but it is not a good test of the model.

U + Cm Experiment

Because the curium nucleus is more fissile than the uranium nucleus, less excitation energy should be needed to induce fission in the curium-like product from a deep-inelastic reaction. Hence, the T_f for the curium-like reaction product may be a more sensitive function of the excitation energy. Consequently, measurements of $P_{K, \text{two-body}}$ and $P_{K, \text{three-body}}$ for U + Cm could show distinct differences because of the variation of T_f .

Additionally, the time-delay effect has never been measured in a high-Z asymmetric collision because, at lower Z, the internal conversion usually swamps the effect. However, in U + Cm collisions, this should not be the case because of the very high Z of the collision partners. We, therefore, decided to investigate the reaction and fission times of U + Cm collisions.

For the experiment, a 8.5-MeV/u uranium beam was provided by Lawrence Berkeley Laboratory's Super Heavy-Ion Linear Accelerator (SuperHILAC). This beam impinged on a ^{248}Cm target that was $660 \mu\text{g}/\text{cm}^2$ thick. The photons and particles emitted were measured in various solid-state and gas detectors. To distinguish the intact

Figure 5. Calculated $P_{K, \text{two-body}}$ compared with $P_{K, \text{three-body}}$ as a function of the TKEL where the fission time is sensitive to the TKEL within the measurable range.

uranium and curium reaction products from the fission fragments, we used two large solid-angle particle detectors: an ionization chamber and a parallel-plate avalanche counter (PPAC, Fig. 6).

The radial ionization chamber is centered at 40 deg on one side of the beam and covers an angular range of ± 14.5 deg. This detector is position sensitive for in-plane and out-of-plane angles and has three energy-loss sections (ΔE_1 , ΔE_2 , E_{rest}). It is filled with a gas mixture of 90% argon and 10% methane at sufficient pressure to stop the highest energy

scattered particle in the E_{rest} section of the detector. The length of the two ΔE sections maximizes the difference of the integrated dE/dx between a reaction product and a fission fragment. Figure 7, a subset of the data, shows the degree of particle identification used. Frames 1, 2, and 3 of this figure are energy-loss data from the ionization chamber. The data are plotted to show the separation of the fission fragments from the reaction products. In frames 1 and 2, the reaction products appear as the dark arcing line, and the fission fragments are the

dense island of data in the lower left quadrant of the frame. Frame 3 shows the correlation between the two front ΔE sections. The data are plotted in a linear fashion that separates contaminants, fission fragments, and reaction products. Frame 4 shows the data accepted by the ionization chamber and is plotted as a function of in-plane and out-of-plane angle. The three bars that support the ionization chamber's window are apparent because they mask the incident particles.

The PPAC measures in-plane and out-of-plane position in addition to energy loss (ΔE_{PPAC}). It is centered at 45 deg on the opposite side of the beam from the ionization chamber and subtends ± 20 deg. Frame 7 of Fig. 7 shows the data accepted by the PPAC as a function of position. The dark region is elastic and quasi-elastic data that have corresponding partners in the ionization chamber. Because the data are gated by ionization-chamber events, the band narrows as the in-plane position increases as a result of the decreasing out-of-plane phase space. Therefore, at larger in-plane angles, the out-of-plane acceptance is effectively reduced in the PPAC. When the ionization chamber is gated by the PPAC, its acceptance is similar. The remaining frames of Fig. 7 illustrate other relationships between the detected particles, which served as useful diagnostics.

Various conditions between the PPAC and the ionization chamber can be set to identify reaction products and fission fragments. In the analysis, we typically identify the intact reaction product (either uranium or curium) in the ionization chamber and use the PPAC to determine whether the other product fissioned. The ionization chamber alone can be used to determine the TKEL.

Figure 6. In-plane schematic of the setup for the U + Cm experiment. Both the ionization chamber and the PPAC have two-dimensional position resolution for incident particles. The Ge and NaI detectors are for x and gamma rays.

For x-ray detection, two planar, intrinsic germanium x-ray detectors were positioned 180 deg from the center of each particle detector (Fig. 6). Figure 8 shows typical raw x-ray spectra from a subset of the data. The uranium and curium K x-ray lines and the Coulomb excited gamma-ray lines are apparent. We used two NaI detectors to measure the higher-energy gamma-ray continuum, which is useful in determining the x-ray yield caused by internal conversion. The trigger condition for the experiment required an event in the ionization chamber coincident with an event in one of the photon detectors. This allowed the greatest possible freedom without loss of useful data.

Conclusions

We completed this experiment in late 1989 and have just begun to analyze the data. Our results look promising and should yield information about fission dynamics, deep-inelastic collisions, and even compound nucleus decay. Although the nuclear interaction in this experiment was deep-inelastic, the reaction products from these collisions appear to decay (fission) as compound nuclei. Therefore, we can use compound nucleus theory to determine the fission fraction as a function of the TKEL (L. G. Moretto, Lawrence Berkeley Laboratory, Berkeley, California, private communication, 1988). Furthermore, studies of the K-vacancy production in atomic collisions where the combined atomic number exceeds 137 are one of the best ways to test the relativistic contraction of the quasi-molecular inner-shell wave functions ($1s\sigma$ and $2p\sigma$), which play an important role in all super-heavy atomic collision phenomena.¹⁸

Acknowledgments

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and Lawrence Berkeley Laboratory, Berkeley, California (R. J. McDonald, G. J. Wozniak, A. Belchacem, and Laurie Blumenfeld).

Figure 7. Two-dimensional plots of the U + Cm particle data from the ionization chamber and the PPAC. Plotted parameters are indicated on the axis in the figure.

Figure 8. Typical particle coincident x-ray spectra for a subset of the U + Cm data.

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Plasma/Hydrodynamic Instability Experiments in Preheated, Laser-Accelerated Packages

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When an interface between materials of different density is accelerated, small perturbations can grow into an intermixing of major proportions. For continuous acceleration, this mixing is due to Rayleigh-Taylor (R-T) instabilities,¹ whereas for shocked acceleration, it is due to Richtmyer-Meshkov (R-M) instabilities.² We have nearly completed a series of experiments to investigate shock-induced planar-foil mix at LLNL's Nova laser. In these experiments, two distinct layers of material are driven together, and the effects of instabilities induced at the preheated interface are measured. The penetration of each material into the other is determined after a smooth planar interface has been accelerated by the passage of a shock. This interpenetration is referred to as the mix width. The purpose of these experiments is

to increase our understanding of plasma/hydrodynamic instabilities in a radiation-driven and preheated environment. Under these conditions, it is usually quite difficult to obtain high-quality data with sufficient statistics, but these measurements strive to do just that. Such data can be effectively used to improve the present computational models to the point where we can achieve a high level of predictive capability and reliability.

Usually, the density difference between the two materials is quoted in the context of the Atwood number α , where $\alpha = (\rho_H - \rho_L)/(\rho_H + \rho_L)$. Here, ρ_H and ρ_L refer to the materials at the interface with the acceleration being in the direction from material L to material H. A large α implies a high degree of instability, whereas a small α implies negligible instability. Negative or reverse α

situations should result in no instabilities for R-T, but yield significant instabilities for R-M cases.

Method

The planar-foil package for a high- α experiment must be carefully constructed of a lower-density material pushing a higher-density one. Figure 1 shows the cross section of a typical disk package used in these experiments. The crucial interface is between the thin molybdenum (Mo) layer and the thicker polyphenylene sulfide (PPS) layer. This interface is kept as smooth and distinct as possible for these measurements. The layered PPS/Mo section is fitted into a gold guard ring covered by a thin layer of PyN. This plastic acts as a tamper to help contain the gold. In some cases, the tamper also extends over the Mo layer.

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The intense radiation drive that accelerates the mix package normal to its surface is produced by using 6 to 10 kJ of 0.35- μm light in a 1.0-ns pulsewidth from eight of the ten beams of the Nova laser. As the PPS ablates, the ablation front is preceded by a shock front of about 60 Mbar in magnitude and 50 ps in rise time. This planar shock propagates through the interface, driving the PPS ablator into the Mo payload. With the passage of the shock wave, the package is accelerated to about half its final velocity, and instabilities are induced at the PPS ablator/Mo payload interface. These instabilities result in perturbation growth at the interface, which allows the materials to penetrate each other. This interpenetration produces a region of mixed materials. The time at which the mix width is measured is usually in reference to the point at which the drive begins, unless otherwise stated. The other relevant time is when the shock reaches the material interface and drives the instability. In this experiment, shock breakout usually occurs about 1.2 ns after the drive begins.

After the drive begins, density initially decreases as the package preheats and expands. The passage of the shock then compresses the Mo density to its maximum value, with any later recompression being due to reflected compression waves. After shock breakout at the rear of the foil, the package rapidly decompresses. At this point, the package expands as it moves away from the drive source. Because of the decompression, the density rapidly decreases. After about 4 ns, the density (now $<0.2 \text{ g/cm}^3$) and opacity are such that the package

can be probed with a 2- to 3-keV x-ray backlighter. Timing constraints on the Nova backlighter beams limit the time window in which we can probe the mix to about 9 ns. Figure 2, which shows a calculation of the mean density of

the Mo payload as a function of time, reflects these features.³

It is clear that the mix width evolves in time in a fairly complicated fashion. One-dimensional hydrodynamic calculations shed some light on this evolution.

Figure 1. Cross section of the cylindrically symmetric, final mix package for the PFM1 series. This design exhibits no obvious dishing effects.

Figure 2. Calculation of the mean density of the Mo payload for a PyN-tamped target as a function of time. Mix package is 60- μm PPS, 1.55- μm MO, and 3.3- μm PyN. (J. C. V. Hansom, Atomic Weapons Establishment, private communication, 1989.)

Figure 3. Dynamic simulation of the experiment (shot mix 36, 58.0- μm PPS/1.8- μm Mo) using the LASNEX computer code for an untamped mix package (V. C. Rupert and P. G. Skokowski, Lawrence Livermore National Laboratory, private communication, 1988). Note the interpenetration limits of the PPS and Mo.

Figure 4. Schematic of Nova planar-foil mix experiment. Point-projection spectroscopy is the technique used to backlight and probe the unstable ablator/foil interface region in the shock-accelerated mix package. The actual experiment uses two of these diagnostic arms during each shot.

Figure 3 is an example of a LASNEX calculation (Ref. 3) of the mix development from the time the drive is turned on to 10 ns later for a 58.0- μm PPS/1.8- μm Mo package. The interpenetration due to R-M instabilities occurs at about 1.2 ns. The mix width is "frozen in" after shock breakout and subsequently expands with the package. This interpenetration is shown in the figure and can be compared with our measurements.

Experimental Technique

To measure the mix width, we use point-projection spectroscopy.⁴ After a suitable delay from the drive pulse, a Nova beam with a pulse length of about 200 ps produces a point-like x-ray source (backlighter), which images the mix package onto a Bragg crystal spectrometer. The crystal acts as a mirror and, combined with the point-like source, projects an image of the mix package onto the focal plane as shown in Fig. 4. Energy is dispersed along one axis of the focal plane, while the other axis is purely spatial. The two-dimensional image allows us to spatially analyze the mix, while the absorption features of the ablator and payload quantify the material interpenetration.

The absorption features used in the experiment are shown schematically in Fig. 5. From these features, we determine penetration values from the detectable limits of the S K-absorption lines into the Mo and of the Mo L-absorption lines into the PPS. The extent of this interpenetration defines the total mix width. Each shot has two data channels like the one shown in Fig. 4. This double data-channel/double backlighter capability enables us to obtain two views of the mix

package at the same time or, by staggering the backlighter delay, to obtain two views at different times. We also have the option of modifying one of the spectrometers to get a different perspective of the mix (as is explained below). With double backlighting, these experiments are some of the most complicated performed at Nova.

Many Nova shots were conducted before we were able to develop this series of planar foil mix experiments (PFM1) into a useful experiment. The early developmental shots dealt with such issues as tilting and dishing of the mix package, effects that tend to mimic real instability-induced mix. However, the double backlighting technique presently used and the fact that point-projection spectroscopy yields a two-dimensional image of the package made these effects obvious in one or both data channels if they existed. Refinements of the mix package design (to that shown in Fig. 1) minimized the above effects, and they are no longer considered a problem.

Since that point, we have performed shots investigating high-mix packages, low-mix packages, and edge effects. It became necessary to reduce the drive energy to obviate possible effects of recompression of the mix region produced by reflected shocks in the package, so there are data at higher and lower mean drive temperatures. We performed 18 shots in FY 1989 alone, nearly completing the PFM1 series of experiments. What remains to be done are several definitive null shots at the lower drive temperature and undispersed imaging of the mix package. These issues are discussed, and preliminary results are presented.

High-Mix Measurements

For the PPS/Mo package, α is large, so these targets are the basis for our high-mix experiments. The package was accelerated by radiation drive in a high and low range that corresponds to total mean laser energies of 5.3 and 6.9 kJ, respectively. We have high-mix data from 5.0 to 8.5 ns for the lower drive and from 6.0 to 8.9 ns for the higher

Figure 5. Schematic of the point-projection spectroscopy image for the normal spectrometer. The spectral features are used to quantify the mix region, which is experimentally defined as the detectable limit of penetration of the Mo to that of the S.

Figure 6. Typical high-mix point-projection spectrometry image data at the lower drive for backlighter delay times of (a) 6.0 and (c) 8.5 ns. (b) and (d) show the density distribution and material interpenetration derived from (a) and (c), respectively. The measured mix widths are indicated for both shots. Limits of detection are also shown for Mo (circle) and for PPS (triangle).

drive. These data consistently show more than 100 μm of mix as defined by the material interpenetration discussed above. Of this, we can attribute about 30 to 40 μm to experimental effects (e.g., motion blurring, finite backlighter source size, digital smoothing), which leaves about 60 μm of real measurable mix. To first order, the calculated mix width (V. C. Rupert, Lawrence Livermore National Laboratory, and J. C. V. Hansom and D. L. Youngs, Atomic Weapons Establishment, private communications, 1989) agrees with our measurements; however, to constrain various models, we must systematically determine the mix width within the time window where we can take data. This is also necessary to understand the physics and make a good comparison with the calculations.

Our present mix data clearly show the accelerated package and the strong absorption features of the Mo and S. The data even show the energy shift of the S line as it crosses the hot ablation front, which changes the opacity of the PPS. In Fig. 6a and c, we see reduced image data from two shots at early (6.0 ns) and late (8.5 ns) times. The bent, cane-like object in the images is a fiducial used to check the space scale. These images have been enhanced with a false color set so that dark blue represents a transmission of one. Figure 6b and d are the corresponding areal density distributions of the ablator and payload plotted as a function of the distance from the original position of the package (displacement). The conversion from transmission to areal density is made assuming cold opacities. The limits of detection for the Mo and PPS are indicated by the circles and triangles, respectively. For both shots, the low-density tail of PPS extending

into the Mo is probably due to edge effects and not shock-induced mix (V. C. Rupert and P. G. Skokowski, Lawrence Livermore National Laboratory, private communication, 1988). The measured mix widths are indicated in the figure.

Control Experiments

Low-Mix Experiments. To determine the experimental resolution, we also ran low-mix experiments using low- α packages where the mix resulting from instabilities is calculated to be less than 20 μm . In these targets, the Mo layer shown in Fig. 1 is replaced with a thicker (15- μm) chlorinated plastic payload (polychlorostyrene) with a density only 6% from that of the PPS ablator. Because the low-mix experiments should show a fairly clean interface (negligible mix overlap), they are also useful in confirming the value of the radiation drive. The interface is smeared into a mix region, so a cleaner interface provides a better-defined reference on the upper limit of the PPS displacement. This can be used in calculations to determine the drive it would take to accelerate the material to that location in time. Because the calculation can only be done to the accuracy of the location of the interface, the low-mix experiments are important.

The measured mix width in some of the the low-mix shots is less than 40 μm , which is close to the system resolution. We are analyzing most of the low-mix data, and we still need data at the lower drive to make a definitive statement. If all of the mix measured in these shots can be attributed to system resolution, then this control experiment suggests that the high-mix data are not an artifact of edge or other spurious effects. However, because of drastic differences in the hydrodynamic behavior of the low- and high-mix package payloads, a quantitative study of edge effects must be done before they can be excluded.

Lateral Expansion Measurements. Our planar foil mix investigations have three major, confounding effects: dishing (discussed above), payload trailing, and ablator blow-by (see Fig. 7). Trailing and blow-by, which are not as easily identified as dishing, can compromise the experiment if they are sufficiently dense. Detailed measurements of the lateral expansion of the mix package are necessary to accurately ascertain their effects. During FY 1989, we performed such measurements by modifying one of the point-projection spectrometers to operate when rotated by 90 deg while using a normally oriented

Figure 7. Package effects that could mimic mix.

spectrometer in the other data channel. This method enabled us to analyze the lateral expansion and measure the mix in the same shot.

For the normal and rotated data channels, the two-dimensional image is essentially the same, but

the spectral absorption features run parallel rather than perpendicular to the interface in the rotated channel. Figure 8 schematically illustrates this (and can be compared with Fig. 5). Because the strength of the absorption feature depends

on the material's density and opacity in addition to the chord length through the mix package, ablator material blowing by the payload would show up as a strong line extending well beyond the limits of the package, as would payload material trailing the package.

Figure 9a shows the result of a typical high-mix shot measuring the lateral expansion (the other channel measured the image seen in Fig. 6a). In this shot, the S absorption edge is set to be approximately in the center of the mix region, and the lateral expansion of the S shows no gross blow-by of ablator material. Figure 9b shows the PPS areal-density distribution in addition to a transmission lineout on the S-absorption line. The symmetry of both the transmission and density distribution affirms the cylindrical symmetry of the driven package in addition to the lack of any significant blow-by. Other shots in this

Figure 8. Schematic of the point-projection spectroscopy image for the modified rotated spectrometer. Whereas the normal spectrometer uses the spectral lines to quantify the mix region (as in Fig. 5), the rotated spectrometer uses these lines to quantify the lateral expansion.

Figure 9. Lateral expansion data from mix shot 36, SIM 2 at 6.0-ns backlighter delay. (a) Typical point-projection spectroscopy image for a rotated spectrometer data channel. The S absorption line measures PPS lateral expansion in the center of the mix region. Because the Mo lines are well into the PPS ablator region, they are not seen. (b) Transmission on the S line and derived PPS density distribution.

series analyzed the lateral expansion of the PPS and Mo at different times. In all cases, we did not see any indication of significant PPS blowing by the Mo payload or of Mo trailing about the PPS.

We performed several shots taking data on the lateral expansion of the PPS ablator and/or Mo payload at different places in the package, but none of these data show any significant blow-by or trailing to confound the measurement. In addition, all of the lateral expansion data are consistent. In fact, the only evidence of any blow-by is the low-density tail of the PPS distribution into the Mo shown in Fig. 6. These tails show up on some of the high-mix data, and one explanation for them is a low-density sheath of PPS blowing by the Mo payload. Two-dimensional modeling (V. C. Rupert, Lawrence Livermore National Laboratory, private communication, 1988) of the mix experiment shows such a sheath of PPS, which causes a similar low-density tail in the resulting distribution. However, the density is low enough that it has negligible influence on the mix measurement.

Discussion of the Data

Because we noted some shot-to-shot changes in the total laser energy, either the data should be normalized to the mean energy, or separate calculations should be done for each shot. To constrain the calculation, we found it better to normalize the data so they will effectively represent the same drive. Figure 10 is a preliminary version of the data that attempts to map the penetration and hydrodynamics. Only a subset of the high-mix data is plotted. Furthermore, these data have not been normalized to the mean laser drive energies.

However, the figure does show that the measured interpenetration follows a pattern similar to that calculated, with some exceptions. A more quantitative statement cannot be made until the appropriate corrections and normalizations have been applied to the final data set.

In Fig. 10, the black circles and blue diamonds are data for the higher laser energy, and the open circles and triangles are the lower-drive data. The errors in time are taken to be the width of the backlighter pulse and position errors owing to system resolution. The higher-laser-energy data include the addition of a 3.3- μm PyN tamper over the Mo foil in the

experiment. By comparing this final data set to the untamped low-drive data, we hope to be able to make a statement on the effect of a tamper and changes in drive temperature on mix. At present, it is not clear whether the higher-drive data have serious recompression problems, as is indicated by some of the modeling (J. C. V. Hansom, Atomic Weapons Establishment, private communication, 1989).

X-Ray Preheat

In these types of laser-driven plasma/hydrodynamic experiments, we can vary the degree of preheat suffered by the interface to

Figure 10. Preliminary penetration/hydrodynamic map for all currently analyzed data. Penetration limits are plotted for comparison to calculated values. Data have not been normalized to a particular drive. Indicated errors are due to backlighter duration (200 ps) and system resolution (40 μm). The black line is a least-squares fit to the Mo data, and the blue line is a fit to the PPS data.

Figure 11. Hydrodynamic calculation of the radiatively driven mix package (J. C. V. Hansom, Atomic Weapons Establishment, private communication, 1989). (a) The calculation to 1.0 ns shows the effect of the preheat on the Mo and PPS/Mo interface before the shock break-out. (b) At shock break-out, the R-M instabilities induce interpenetration, and a mix region develops. The mix region and package then decompress. The calculation does not account for any mixing of the PyN tamper with the rest of the package.

ascertain how it affects the instability. This preheat causes the foil interface to expand before the shock passes, resulting in a smoother density gradient from one material to the next, as shown in Fig. 11a. Figure 11a and b are calculations (J. C. V. Hansom, Atomic Weapons Establishment, private communication, 1989) of the hydrodynamics out to 1.0 ns and 2.0 ns, respectively, of the high-drive data with the inclusion of a tamper. According to this calculation, at about 1.2 ns, the shock breaks out, and the Mo foil has expanded by more than a factor of 2. By decreasing the density of the Mo and changing the density gradient from an abrupt step to a smoother transition, we greatly reduce the mix caused by the shock. However, the effect of preheat on mix is a rather open question because other calculations³ do not show such a drastic change in the induced mix width as a function of preheat. In any event, in addition to possibly affecting the amount of mix, the preheating in this experiment clearly complicates any study involving mix as a function of interface surface texture. A low-preheat experiment should allow us to study the effect of surface finish, seeded perturbations, and modulated perturbations because they would not be washed out prior to shock passage.

Conclusions

In these planar-foil mix experiments, we have measured about 100 μm of material interpenetration in high- α targets. Because 30 to 40 μm of this can be attributed to system resolution, there appears to be $\geq 60 \mu\text{m}$ of real mix that results from R-M instabilities. Although analysis is still in the preliminary stages, the high-mix data seem consistent. From the data, we can

derive a map of the hydrodynamics and material interpenetration from 5 to 9 ns after the drive is turned on. Low- α control experiments have not yet yielded conclusive results and are being pursued. Calculations have shown rough agreement with the high-mix experimental results and are also in progress. We have investigated a host of effects that could mimic mix in the experiment and have determined them to be negligible. In particular, we conducted an in-depth investigation of the lateral expansion of the mix package and did not measure any significant blow-by of material. On the basis of these studies, we believe the measured mix is the result of accelerated material intermixing and not edge effects. We have performed these experiments with a significant amount of x-ray preheating. To assess the effect of preheat, we must perform a series of experiments where the preheat is lowered so the interface is colder and more representative of a true density jump.

We are designing the next generation of plasma/hydrodynamic instability experiments, which

would radically change the experiment. These experiments would study the mix in compressed matter. The crucial element is, of course, the target and mix package, but a higher-energy backlighter of sufficient intensity would improve the experiment and help in the target design. Such a backlighter and perhaps different diagnostics would have to be developed. We are already starting to look into new target/mix package designs. We are also developing a backlighter that is continuous over a 1-keV range in the x-ray energy region from 7 to 10 keV. If successful, it could have a major impact on the next-generation experiment.

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Experimental Modeling, Design, and Analysis

Monte Carlo Modeling of Opacity and Non-LTE Atomic Kinetics

B. G. Wilson, J. R. Albritton, and D. A. Liberman

The absorption and emission of radiation by atomic electrons are important in the calculation of energy transport in hot, dense plasmas. The principal obstacle in calculating these plasma properties is the enormous number of configurations of bound electrons that must be considered. An exhaustive search over all possible configurations would be prohibitively time-consuming. To only consider a preselected ensemble of the most important configurations presumes a knowledge of the excitation and ionization distribution of the plasma ions. Such a priori characterizations are difficult, especially in situations where the plasma is out of local thermodynamic equilibrium (LTE). Because of these difficulties, calculations often relied on approximate "average-atom" descriptions.¹ To overcome the limitations of such an approach, we developed a Monte Carlo detailed

configuration accounting (MCDCA) scheme to calculate the opacity and emissivity of hot, dense plasmas. Its principal virtue is its ability to realize solutions efficiently (an advantage over exhaustive configuration search schemes) and automatically (an advantage over limited or preselected ensembles of configurations). It is equally capable of describing steady-state non-LTE as well as LTE plasmas.

Detailed Configuration Accounting

Detailed configuration accounting idealizes a plasma as a collection of individual ions (that is, the bound electrons are not in quasi-molecular orbitals), with each ion in a definite state and labeled by the configuration of the bound electrons. In our model, a configuration is a set of occupancies of relativistic independent particle subshells (Fig. 1). The free electrons, among

which the ions move, affect the ionic structure and limit the number of subshells through the phenomenon of continuum lowering.²

To describe the state of such a plasma, we must know how the ions are distributed over the set of possible configurations. The Monte Carlo method automatically searches for and finds the most probable configurations. To calculate the opacity, the code considers each found configuration in turn and computes the allowed excitations that can absorb radiation, all weighted by the probability that the initial configuration is occupied. Figure 2a shows an example of an iron opacity provided by the MCDCA code. The detail should be contrasted with the average atom results of Fig. 2b, which considers only one electron transition from a single (fictitious) average configuration that is statistically broadened to account for the many detailed configurations.

Figure 1. A sample configuration in the j-j coupling scheme. Each subshell, which is labeled by $[n,l,j]$, can hold $2j + 1$ electrons and is here pictured as a stack of boxes.

The Monte Carlo Method

The Monte Carlo technique^{3,4} computes the state of the plasma by tracking the configuration history of a test ion in the ambient plasma and radiation field on an atomic time scale. It starts from an arbitrary initial configuration, then calculates the rate for each process by which the configuration can change. The code then chooses a process randomly, but the selection process is biased such that those with the largest rates are more probable. This is done by segmenting the numerical interval $[0,1]$ into pieces that are proportional to the size of the rates, then randomly pointing in the interval. In the general non-LTE case, we then determine the physical time the ion exists before changing from this initial configuration. As in nature, this time is randomly determined from an exponential decay law for the probability that the ion has made no transition. The decay rate is obtained as the sum of rates for all processes by which the configuration can change. The test ion is then advanced to the new configuration, and the algorithm is repeated indefinitely while we record the configurations visited and accumulate the total time spent in each configuration. We assume that our system is ergodic and that the test ion randomly, but rapidly, wanders through configuration space and explores the most probable regions. After a sufficiently long run, we can then equate the time average of this test particle with the ensemble average of the plasma.

The physics governing dense plasmas are included in the Monte Carlo method through the calculation of the rates. In the general non-LTE situation, processes should include radiative ionization and recombination, collisional ionization and recombination, bound-bound

radiative excitations and de-excitations, and collisional excitation and de-excitation of bound-bound transitions as well as Auger and resonant capture transitions. With this last category, dielectronic recombination processes are included in their most general form because the Monte Carlo method obviates the need for preselecting the radiative stabilization processes.

Code Development

Obviously, the expense of the calculation is in the generation of the required rates. This cost is mitigated by two factors. First, the configurational dependence of most rates can be obtained by a series expansion in occupation numbers about some reference configuration,⁵ often parametrically through the transition energy. Second, the rates for each

configuration need be computed only once and then stored. When a configuration is revisited in the random "walk," the rates are retrieved. The test ion eventually walks in a somewhat bounded configuration space, so we can economically make computer runs of many events by using efficient look-up algorithms. To offset the memory needed to store every rate, we can lump unlikely processes. In the rare occurrence that a lumped process is randomly chosen, we can expand (regenerate) those rates at will, thereby trading a small amount of speed for an often large amount of memory. By running the MCDCA program for even longer random walks, observables such as the ionization balance or the spectral opacity (which are primarily determined by the most probable configurations) are seen to converge rapidly.

Figure 2. (a) The LTE opacity for iron at plasma conditions of 160-eV temperature and 0.01-g/cm^3 density as calculated by the MCDCA code over the frequency range of 0 to 3 keV. (b) The LTE opacity for iron at the conditions of (a) as calculated from the average-atom code MURKY. The scale is such that the plot can be directly overlayed on (a) for comparison. The various extra lines denote the individual contribution from bound-bound, bound-free, and free-free processes.

Table 1. Charge-state distribution for selenium foil at an electron temperature of 700 eV, an ion temperature of 350 eV, no external radiation field, and a free-electron density of $5 \times 10^{20} \text{ cm}^{-3}$.

Charge state	Dielectronic excluded (%)	Dielectronic included (%)
Nitrogen-like	3.10	—
Oxygen-like	14.60	0.14
Fluorine-like	33.08	2.54
Neon-like	43.08	49.28
Sodium-like	5.54	37.21
Magnesium-like	0.37	9.34
Aluminum-like	—	1.32

Figure 3. (a) The steady-state non-LTE opacity for selenium at an electron temperature of 700 eV, ion temperature of 350 eV, and free-electron density of $5 \times 10^{20} \text{ cm}^{-3}$ after the pumping laser has fired (i.e., assuming no external radiation field) as calculated by the MCDCA code. We considered the physical processes of radiative excitation and ionization and collisional excitation and ionization (along with their inverse process). No dielectronic processes were included. Dips in the opacity (cut off below by the log scale) denote regions of x-ray lasing gain. (b) The opacity calculated for selenium at the plasma conditions of (a) but including dielectronic processes.

Model Calculations

Among the many applications of the MCDCA code is the investigation of dielectronic recombination processes on the charge-state balance of plasmas. Table 1 shows the non-LTE ionization balance for selenium foil targets during x-ray lasing conditions if we neglect dielectronic processes. The companion Fig. 3a plots the calculated opacity for selenium (corrected by stimulated emission). The lines dipping in the figure denote narrow regions where x-ray lasing gain occurs, and each feature agrees with configuration averages of more detailed treatments. Table 1 shows that, if we include dielectronic processes, the overall ionization state of the plasma has one more bound electron, whereas the second most dominant charge state changes from being more ionized to less ionized. In Fig. 3b, the opacity now shows a turtle-like hump in the spectrum, but, interestingly, the positions of the dominant lasing regions and their gains are relatively unaffected.

Besides modeling applications, the MCDCA code will be used to test the veracity of statistical approximations for calculating opacity. As an example, Fig. 4a presents MCDCA results for steady-state non-LTE conditions typical of the Nova gold disk x-ray conversion experiments, which can be compared (Fig. 4b) to the statistical configuration accounting (SCA) method available in LASNEX.

Future Developments

We will pursue several areas of code development in the near future to expand the utility of the MCDCA code to modelers. We plan to include (if not rigorously, at least in some computationally efficient approximation) term structure in the configuration transitions. We also hope to extend our capabilities to describe

higher Rydberg states by successively compacting the detail of the description of states, starting from a relativistic subshell description at low n , to a nonrelativistic shell description at intermediate n , until a hydrogenic description of high- n states suffices. For non-LTE applications, we want to input arbitrary (non-Planckian) radiation fields. Also, we are investigating algorithms to make distorted-wave Auger rate calculations competitive with the faster (semi-analytic) Coulomb wave approximations now used.

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Figure 4. The steady-state non-LTE opacity for gold at conditions for Nova x-ray conversion experiments: 1-keV electron temperature and free-electron density of 10^{22} cm^{-3} , with a radiation field approximated by a Planckian at a temperature of 200 eV. (b) The opacity of gold for the conditions of (a) as computed by the SCA option of LASNEX.

Atomic Modeling and X-Ray Astrophysics

A. L. Osterheld, W. H. Goldstein, D. A. Liedahl,* and S. M. Kahn*

Spectroscopy is a powerful tool for diagnosing plasmas under a wide variety of conditions. Tools for modeling plasma emission were first developed in the 1960s to interpret x-ray emission from solar flares. More recently, advances in modeling have been motivated by an interest in magnetic fusion, inertial confinement fusion, and x-ray lasers, and by the development of laboratory sources of hot, dense plasmas.

The Prompt Diagnostics Program has considerable expertise in modeling laboratory and weapons plasmas. We are engaged in a collaboration to use these modeling capabilities to study astrophysical plasmas, which will, thus, allow us to study plasmas that are difficult to create in the laboratory.

To date, our work in modeling has focused on:

- Applying a quasi-steady-state approach to an evolving plasma.
- Improving the accuracy of calculations of fundamental atomic rates required for plasma modeling.
- Developing an extremely detailed collisional-radiative model for studying emission from iron ions in a collision-dominated plasma.
- Enhancing traditional collisional-radiative methods to describe the photodriven plasmas that exist in x-ray binary systems.

In the future, we will also investigate supernova remnants and active galactic nuclei.

Collisional-Radiative Models and the Quasi-Steady-State Approximation

Atomic-level populations of an evolving plasma are described in a collisional-radiative model by the following rate equation:

$$\frac{dn_i}{dt} = \sum_k n_k R_{ik} - n_i \sum_k R_{ik}, \quad (1)$$

where R_{ik} is a rate coefficient for a transition from level i to k . R_{ik} includes collisional excitations and de-excitations, radiative decays, collisional ionizations and recombinations, and radiative and dielectronic recombinations.

Applications of these equations to complicated systems have typically been limited by the number of atomic levels treated in the calculation and by the quality of the atomic rate coefficients. To address these problems, we have implemented techniques that quickly and accurately calculate large numbers of energy levels and transition rates. This information is used to investigate laboratory and weapons plasmas. Our techniques, discussed below, are a great improvement over those generally available in the astrophysics community.

The straightforward integration of the rate equations coupled to the hydrodynamic and energy-balance equations is costly. Furthermore, it often yields little insight in systems for which the driving mechanisms are not well characterized. The level

kinetics are typically solved in steady state. This approach works well for a hot plasma near ionization equilibrium, but it often yields inaccurate and confusing results in a nonequilibrium plasma. The time scales for the excited states to equilibrate are often much shorter than the time scales for changes in plasma conditions or in the ionization balance. We solve the rate equations for such plasmas in the quasi-steady-state approximation. The ground-state-level populations are treated as parameters, and the excited-state equations are solved in steady state, including excitation mechanisms resulting from the nonequilibrium ionization balance. This approach allows nonequilibrium plasmas to be treated without introducing time dependence. We infer the ionization balance from observed x-ray intensities. With this ionization balance, our model describes the line-excitation mechanisms correctly, in marked contrast to the ionization-equilibrium approximation.

The quasi-steady-state approximation is ideally suited to spectral diagnostics of plasmas. We have successfully used this approach to analyze x-ray spectra from a variety of laboratory plasma sources. It is similarly useful for diagnosing astrophysical plasmas, particularly in novel environments for which plasma conditions, driving-energy sources, and line-formation mechanisms are poorly understood, or in which the plasma is far from ionization equilibrium.

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Atomic Data for Modeling

Typical plasma-modeling calculations treat the populations of hundreds of levels and require rate coefficients for thousands of atomic transitions. Until recently, the calculation of these rates—particularly the collisional excitation rates required to treat intermediate electron densities—was prohibitively expensive.

We obtain the atomic parameters for our models from the Hebrew University–Lawrence Livermore Atomic Code (HULLAC). This package was originally developed at Hebrew University of Jerusalem. We have collaborated with Hebrew University to improve and enhance the HULLAC code at LLNL over the past several years. Energy levels, radiative and Auger transition rates, and distorted-wave electron-impact excitation cross sections are calculated in the relativistic, multiconfigurational, parametric potential model.^{1–3} The cross-section calculation uses a powerful factorization theorem and a physically motivated interpolation scheme to reduce computer time requirements by several orders of magnitude.⁴ This unique combination of accuracy and speed is ideal for plasma-modeling applications.

Resonant Excitation in Fe XVII

Resonant excitation refers to the enhancement of electron-impact excitation arising from electron capture to states lying in the continuum, followed by subsequent autoionization. Because the temperature dependence of this process differs from that of direct excitation, accurate calculations of this effect are important for plasma diagnostics. We recently enhanced the HULLAC package to treat Auger transitions, and we calculated resonant-excitation-rate coefficients for the $2p^53s$ and $2p^53p$ levels

in Fe XVII in the isolated-resonance approximation.⁵ Thousands of autoionizing resonances contribute to these rate coefficients. Previous calculations used configuration-averaged approaches, which incorrectly determined energetically allowed autoionization channels.

Our calculated resonant-excitation rates are considerably lower than those currently used to interpret Fe XVII emission from astrophysical sources. This result has serious implications for the interpretation of solar-flare data, where the $3s-2p$ Fe XVII transition has been of major importance.

The L-Shell Spectra of Ionized Iron

Because of the importance of the x-ray spectra of L-shell iron in solar flares and other astrophysical x-ray sources, we used the HULLAC package to construct a detailed atomic model⁶ of Fe XVI–XIX. This model includes all important radiative and collisional transitions as well as detailed calculations of resonant-excitation and dielectronic-recombination rates.

When we compared our model calculations with high-resolution spectral data from solar flares and active regions, we discovered several misidentified and unidentified x-ray transitions. Our analysis has shed doubt on some currently used plasma diagnostics. Ratios of $3d-2p$ transitions from different charge states, Fe XVII and Fe XVIII, for example, are frequently used to estimate electron temperature. This practice is dangerous, as it requires an accurate calculation of the complex processes governing the ionization balance and assumes that the plasma has reached ionization equilibrium. Using lines from

Fe XVI–XVIII, we are developing a technique that allows us to simultaneously determine the electron temperature and the relative fractions of Fe XVII and Fe XVIII in the line-emitting region.

Photoionized Nebulae

High-quality spectroscopic data are available from solar flares and active regions. The existence of these data has encouraged the development of a number of plasma-emission codes that model the x-ray spectra of optically thin, collision-driven plasmas. Although these tools are often used to analyze spectra from other cosmic sources, the typical assumption of collisional-radiative equilibrium renders them inapplicable in many important astrophysical systems. A striking example is provided by photoionized nebulae around x-ray binary systems. The x-ray spectra presently available from these systems have generally resisted unambiguous interpretation with these models.

Line-excitation mechanisms in photoionized plasmas differ dramatically from those in conventional, collisionally driven plasmas.⁷ In an equilibrium collisional plasma, the excitation processes and ionization balance are both characterized by the electron temperature. This fact ensures that the excitation of levels having x-ray transitions is dominated by collisional excitation. In a strongly photodriven plasma, however, the flux of ionizing radiation produces a charge-state distribution significantly overionized relative to the local electron temperature. In this situation, recombination and recombination-cascades are the dominant line-excitation mechanisms. These phenomena produce striking qualitative differences in the features of the x-ray

spectra, as shown in Fig. 1. This figure compares model Fe XVI–XIX spectra under conditions appropriate to two environments: a hot coronal plasma, and an x-ray photoionized nebula (XPN).⁷ The 3d–2p transitions arising from strong impact-excitation rates dominate the coronal

spectra but have largely disappeared from the XPN spectra. At the low XPN temperature, the collisional excitation rates are vanishingly small, while the photoionization-driven ionization balance produces strong line excitation by recombination and cascades.

This example demonstrates how applying standard plasma-emission codes to XPNs can easily lead to line misidentifications and subsequent errors in estimates of plasma conditions. For example, misidentifying the 1.5-nm Fe XIX feature in the XPN spectra as the Fe XVII 3d–2p transition would lead to a gross error in the inferred electron temperature. A feature at this wavelength that is present in available spectroscopic data from low-mass x-ray binary systems^{8,9} has escaped unambiguous interpretation in the context of coronal-emission models. In addition, a feature observed at 1.6 nm had been identified as the O VIII Lyman- β transition, even though the Lyman- α transition was not observed. Our analysis suggests that this feature is 3s–2p emission from Fe XVIII.

Future Work

The work summarized here is ongoing. We are completing our investigation of charge-state and temperature diagnostics in coronal plasmas. These diagnostics will make timely contributions to the study of solar flares and active regions as the next solar maximum approaches. Our investigation of XPNs has revealed qualitative signatures of photoionized plasmas. We are, therefore, studying quantitative diagnostics. In addition, we plan to investigate young supernova remnants, which are thought to be in an ionizing phase and which may be non-Maxwellian. Satellite missions planned for this decade will provide high-quality x-ray spectra from a variety of cosmic environments. Those data will rival data now gathered from the sun. The spectroscopic study of these objects will contribute substantially to our understanding of cosmic x-ray sources.

Figure 1. Comparison of model emission spectra for Fe XVI–XIX under conditions appropriate to (a) coronal equilibrium, where $kT_e = 500$ eV and $n_e = 10^{11}$ cm⁻³ (T_e is electron temperature, and n_e is electron density), and (b) x-ray photoionized nebulae, where $kT_e = 10$ eV and $n_e = 10^{11}$ cm⁻³. The emissivity scale is arbitrary. This example demonstrates how the application of standard plasma-emission codes to XPNs can easily lead to line misidentifications and subsequent errors in estimates of plasma conditions.

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Streak-Camera Image Processing on the Macintosh II

R. M. Buck and E. M. Lent

The electronic streak camera is used heavily by experimental physicists of the Prompt Diagnostics Program to record fast pulses. In a typical downhole experiment, illustrated in Fig. 1, many detectors are set up to measure a fast transient pulse of radiation. The output of each radiation detector is converted to a light signal and transmitted over an optical fiber to the streak camera, where the ends of the fibers are arrayed at the entrance slit. Light from each fiber forms a spot on the camera's photocathode. The electrons emitted from each spot on the photocathode are focused by electromagnetic fields onto a phosphor screen placed at the image plane of the camera. In operation, the spots are swept across the screen by a ramp voltage applied to the deflection structure of the camera, creating a linear streak for each fiber.

Knowing the sweep speed of the camera, we convert the linear displacement along each streak to elapsed time. Time resolutions of better than 1 ns have been achieved in laboratory and field experiments. The light emitted by the phosphor screen is amplified by an electron microchannel plate, then recorded

electronically by a densely packed array of charge-coupled diodes.

Figure 2 shows a typical streak-camera record. To analyze an individual streak, one computes the time and the integrated light intensity for each point along the streak. The integrated light intensity can be converted to optical power at the streak-camera input by means of a set of calibration streaks, then to a radiation level at the detector. This article describes the steps used to transform each streak into a power-time history at the input window through use of processing software running on the Apple Macintosh II computer.

Processing Software

We selected the Apple Macintosh II computer as the office and laboratory workstation for the physicists of the Prompt Diagnostics Program. This computer is well suited for processing images—particularly those from streak cameras—when it is outfitted with 8 Mbyte of memory, a 16- or 19-in. color monitor, and, optionally, a floating-point accelerator board.

We use three Macintosh codes in streak-camera image processing. These codes are discussed in detail below. The IMAGE L code displays the image record and allows the user

Figure 1. Schematic of a typical experiment in which a streak camera records fast pulses of radiation from multiple detectors.

to locate image features and extract subimages and lineouts. The STREAKPRO code performs geometric-distortion correction, automated streak extraction, and amplitude calibration. The TCAL code analyzes the timing tracks of the camera and assigns times to each streak point.

IMAGE L Code. The IMAGE L code is a Macintosh II program for acquiring, enhancing, analyzing, editing, animating, and pseudocoloring gray-scale or color images. A modified version, named IMAGE L, was developed by the Prompt Diagnostics Program's Code Development Group (CDG) to work with 16- and 32-bit streak-camera images. IMAGE L produces histograms; performs contrast enhancement, density profiling, and digital filtering; and can compute the

average density along rows, columns, or diagonal lines of a user-defined region of interest. IMAGE L provides many MacPaint-like editing functions, including the capability to draw lines, rectangles, and ovals and to write text. Density profiles and histograms may be output into SOCKIT files or tab-delimited files for input to the SODA signal-processing code or other processing and plotting codes such as Excel and CricketGraf. Manipulated image files may be stored either in the code's own format or as PICT files, for inclusion in reports and other media. When IMAGE L is used with the STREAKPRO code, it will display any type of image that STREAKPRO can handle, which now includes images in IPIC (IMAGE L format), PDS, Photometric, and Excel formats.

STREAKPRO Code. The CDC developed the STREAKPRO code specifically for processing streak-camera images. (The code's name is an acronym for streak processor.) It works cooperatively with IMAGE L to provide the custom processing steps that are needed to reduce and analyze streak-camera data. The code does not display images itself but links with IMAGE L under Multifinder, so that images opened with STREAKPRO can be immediately displayed by IMAGE L.

The capabilities of STREAKPRO include:

- Unary and binary operations on images.
- Sinc-function interpolation of image rows.
- Creation of a streak map, which locates the column of peak intensity for each streak in a calibration image.
- Automated extraction of streaks from an image, using a previously created streak map to locate streak edges. This feature forms a streak table of integrated streak intensity vs row and streak number.
- Conversion of streak-table row number to time, using the time-conversion file resulting from a run of the TCAL timing code.
- Creation of SODA-format or tab-format files from rows or columns of a streak table.
- Correction for adjacent-channel crosstalk.
- Amplitude calibration by linear interpolation into a set of calibration streaks.
- Dewarping of images to correct for geometric distortion of the camera along the time axis.

TCAL. The TCAL code analyzes the timing tracks of the camera to generate a timing calibration curve. This curve is then applied to each streak to convert displacement along the streak to calibrated time.

Figure 2. Typical streak-camera record. Time resolutions of less than 1 ns have been achieved in laboratory and field experiments.

Streak-Camera Processing Steps

We now discuss the usual streak-camera processing steps, which are image dewarping, streak extraction, and amplitude and time calibration.

Image Dewarping. A streak-camera record is not an image in the photographic sense because it does not reproduce the intensity patterns of a projected three-dimensional object. Rather, it uses the imaging format to record signals from several two-dimensional data channels (fiber-optic power vs time). Therefore, relatively few analytical operations that are truly image processing have to be performed, which greatly reduces the power required of the computer. Image dewarping is the only true image-processing operation for streak-camera data that we discuss here.

Nonuniformities in the electron optics of the streak camera can cause a "pincushion" geometric distortion to appear in the image. Straight lines are imaged by the camera as bowed lines. Unless the bowing distortion, which occurs along the time axis, is corrected, it will produce timing errors during subsequent time-conversion processing.

To reduce geometric distortion, which can be as large as a two-row deviation from linearity, we apply geometric-distortion correction ("dewarping") to the image. First, we measure the bowing distortion in the time direction by repetitively pulsing a laser into the fiber inputs while the camera is streaked. This procedure gives a sequence of lines of dots across the camera, each line formed from simultaneously created dots (Fig. 3). The departure of each dot line from linearity shows the magnitude of the bowing distortion. We accurately determine the overall distortion by fitting a mathematical

Figure 3. Typical record used to measure distortion in streak-camera images caused by nonuniformities in the camera's electron optics. The dots forming each line are created simultaneously, and the departure of each dot from linearity indicates the magnitude of bowing distortion. This information is used in dewarping the streak-camera image.

Figure 4. Result of fitting the polynomial model to the dot-line image shown in Fig. 3.

Figure 5. Illustration of streak extraction, which is the formation of a two-dimensional profile produced by integrating in one direction over the pixels making up the streak. (a) A section of the streak-camera record shown in Fig. 2. The dashed rectangle outlines the part of the timing-comb streak to be extracted. (b) Profile resulting from the extraction as performed by our IMAGE L code.

model of the distortion to all the dot lines at once. Each dot line is fitted with a polynomial model:

$$|Y_j - Y_c| = A_0(r_0) + A_1(r_0)(x_j - x_0) + A_2(r_0)(x_j - x_0)^2, \quad (1)$$

where x_j , Y_j are the centers of the dots in a given dot line, in camera column and row units; Y_c is the row number of the center of the distortion pattern (in general, the distortion pattern is nearly symmetric about a row near the camera center); x_0 is the column number of the intersection of the dot line with the fiducial column (a constant for the image); and r_0 , which is to be determined by the modeling process, is the Y value to be assigned to this dot line, i.e., it is the row number of the dot line in the dewarped image. The A_k s are themselves functions of the variable r_0 :

$$A_0 = r_0, \quad (2)$$

$$A_1 = A_{10} + A_{11}r_0 + A_{12}r_0^2 + A_{a1}, \quad (3)$$

$$A_2 = A_{20} + A_{21}r_0 + A_{22}r_0^2 + A_{a2}, \quad (4)$$

where A_{a1} , A_{a2} are asymmetry coefficients that account for the departure of the distortion pattern from symmetry about $Y = Y_c$. A_{a1} , A_{a2} are nonzero only in the part of the image above $Y = Y_c$.

Each dot line is approximated in this model by a quadratic form whose coefficients are allowed to vary slowly over the camera from top to bottom. Because the model depends on r_0 in a nonlinear way, the equations are solved by an iterative least-squares method to find the best-fit values of the six A_{1k} , A_{2k} coefficients and A_{a1} , A_{a2} . Figure 4 shows the result of fitting the model to the dot-line image in Fig. 3.

Once we determine the model coefficients, any image from the camera can be dewarped by solving the modeling equations at each image point (x, Y) . That is:

$$Y_{\text{dewarped}} = f_0(Y, Y_c, x - x_0, A_0, A_1, A_2). \quad (5)$$

Automated Streak Extraction.

Extracting a streak means forming a two-dimensional profile of a three-dimensional streak by integrating in one direction over the pixels that make up the streak. Figure 5a shows a section of the image displayed in Fig. 2. The dashed rectangle outlines a portion of a timing-comb streak that we want to extract by integrating the pixel values along each row within the rectangle. Figure 5b shows the profile resulting from the extraction as performed by IMAGE L. The abscissa is the row number along the streak, and the ordinate is the average pixel value for each row within the integration rectangle. This process, in which the user must manually place a selection rectangle around each streak desired for extraction, only works well for a few streaks that are well separated and aligned along camera columns. The automated streak-extraction feature of STREAKPRO allows the rapid extraction of many nonlinear streaks simultaneously.

The first step is the creation of a streak map for the image. A streak map is a table of streak-peak column locations, which is given for each row of the image. It is automatically constructed by STREAKPRO from a calibration image in which all fibers are evenly illuminated. The code scans each row of the image to locate the peak pixel value for each streak or, alternatively, the centroid

of each peak. This step produces a map that gives the locus of each streak in the image.

Signal streaks are extracted by applying the streak map as a template over a signal image. All pixels within a specified distance of a streak locus are summed to produce an extracted streak profile. The calibration streaks and the signal streaks must be in registration for this method to be successful.

Streak-Amplitude Calibration.

The streak profile is now in units of pixel value vs distance along the streak, i.e., row units. Applying an amplitude calibration converts the ordinates to optical-power input to the streak camera. This step is performed in STREAKPRO by looking up the profile pixel value in each row, in a previously prepared table of pixel value vs row number for various input powers (see Fig. 6).

Figure 6. Calibration table used to determine optical-power input to the streak camera. Input-power levels are at 0, 2, 5, and 10.

Figure 7. (a) Macintosh display showing the level and tau used in the peak-finding algorithm. (b) Display showing the centroids of each peak. (c) Display showing the data and the resultant fit.

The calibration table itself is generated by processing the streaks produced by calibrated light signals introduced into the camera input slit.

Streak-Time Calibration.

We perform time calibration with the auxiliary code TCAL. TCAL reads a comb file that has been extracted from the streak record. A level used in the peak-finding algorithm is set, and the frequency or tau, which is used for timing, is entered (see Fig. 7a). The centroid of each peak is determined and a time assigned (see Fig. 7b). The resulting channel-vs-time data are fitted to yield the time calibration (see Fig. 7c). The data and the resultant fit can be displayed—in either channel or velocity representations—to show the quality of the fit.

At this point, we either apply the calibration to individual extracted streaks or save the calibration results and read them into STREAKPRO to calibrate the entire streak record. The calibration process includes a velocity correction to the amplitudes in which areas are preserved.

In some cases, a marker signal, which effectively records the velocity variations along the streak, is included with the timing comb. If so, TCAL determines the channel-vs-time data from the comb as before and combines them, in a least-squares sense, with the marker data to obtain a calibration whose velocity information is from the marker and whose times have been adjusted to fit the timing-comb data.

Summary

We have implemented an extensive set of procedures for processing streak-camera images on the Apple Macintosh II computer system. The STREAKPRO processing code, run in conjunction with the IMAGE L image-viewing code, allows the user to perform a sequence of operations necessary to dewarp images and extract, calibrate, correct, and time the streaks in a camera image, using timing information generated by the TCAL code.

These new capabilities have greatly increased the efficiency and convenience of image processing in the Prompt Diagnostics Program. Processing operations have moved from remote time-shared computers, such as the Octopus Crays and the L Division Imaging Research and Development Laboratory's VAX, to Macintosh workstations in the office or laboratory. Enhancements planned for STREAKPRO in FY 1990 include frequency-domain filtering, spatial-domain convolution, and the modeling of streak profiles to improve the precision of streak-power estimates.

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1. The IMAGE code was written by W. Rasband of the National Institutes of Health, Bethesda, MD.

Charged-Particle Transport Features in the COG Code

T. P. Wilcox, Jr.

COG¹ is a Monte Carlo transport code that we wrote for the NTES Directorate to solve detector and background signal problems during nuclear tests. COG is also a general-purpose shielding code and solves criticality calculations. This easy-to-use tool produces accurate results from input data and, unlike many codes of this type, is not affected by built-in approximations that "speed-up" a calculation. The code has been used since FY 1987 and has met design goals.

The original version of COG handled neutrons and photons within the energy ranges of existing cross-section data (100 eV to 100 MeV). In FY 1989, the photon data were extended to include both lower energies (10 eV) and higher energies (100 GeV), and we are incorporating this information with only minor adjustments for physical reactions that exist at the higher energies. The potential to follow charged particles is written into the code's framework. However, we have not yet calculated these particles, and attempts to follow them produce error warnings that terminate the code.

In FY 1989, four groups of COG users asked that charged-particle transport be added. These users included three groups interested in electromagnetic pulse (EMP) calculations. We initially added the ability to indicate the production of electrons from photon reactions at a detector location and to specify the energy, direction, and time history of the electrons. We then transferred the results from this improved code to various EMP codes. To minimize errors in interpolating the results,

we ran several calculations and supplied curve fits. This method was satisfactory for simple calculations, but complicated problems required more detail. We then provided data on a disk file that described three values of direction, three values of position, a time value, particle type, and statistical weight for every electron or positron generated by the photon reactions. The transport codes were then altered to read these data. In all cases, COG simulated charged particles but still could not follow them.

The fourth user group required electron transport calculations and used the EGS4 code developed at the Stanford Linear Accelerator Center (SLAC) in Palo Alto, California.² This code was satisfactory in the beginning, but later problems required the design of more complicated geometries and source descriptions. We placed our upgraded COG geometry package into the fourth group's version of EGS4 and arranged this code to read a COG-written source description file.

Since FY 1985, LLNL's Computational Physics Division has been securing electron data and developing Monte Carlo techniques for transport calculations. We intended to incorporate these into the COG code, but work has slowed because of funding problems. In FY 1989, while waiting for this information, we started to analyze the EGS4 code, which is best for calculating higher-energy electrons and positrons, to understand its operation and data generation. We have also examined codes that contain better physics for lower-energy particles. By

combining the improved COG and upgraded EGS4 codes, we expect to produce a COG program to solve calculations projected for future NTES projects.

We are placing the EGS4 cross-section generator into a version of COG so that the standard COG inputs will define data for electron and positron cross sections. We will next add the Monte Carlo methods that transport charged particles. These methods differ from methods used to follow photons and neutrons because electrons lose only a very small fraction of their energy in a collision. Our goal is to implement these methods in a manner that prevents the user from receiving incorrect answers because of method aspects that he or she does not understand. These techniques of transporting electrons involve only a few additions to the COG geometry package, and most of this implementation is complete.

To conclude our work, we will run a series of calculations on experimentally determined systems. These benchmarks will show that the code and methods employed in it produce satisfactory results.

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High-Quality Image Processing for Atomic and Laser-Physics Applications

C. H. Dittmore

We have devised a system that photographs the performance results of diagnostic devices and related weapons-test data. We collect these data on film as photographic records of oscilloscope traces. Our system consists of a detector, a transmission cable, an oscilloscope, a camera, and various electronic-support equipment. The system's success depends on the performance of these components. Because the end record is photographic film, the quality of the film record will determine the quality and quantity of the data that can be recovered from the experiment. Experimental data that we record on photographic film can be degraded by many factors (e.g., focus, grain, noise, processing, and ionizing radiation).

For many years, we chose a high-speed film (such as Kodak Royal X Pan) because of the limited light output of the cathode-ray tube (CRT). However, with the emergence of the microchannel-plate CRT, the high-speed capability of this film is no longer our main criterion when choosing film. We now look for film that has smaller grain size, higher resolution, a better signal-to-noise ratio, greater maximum density, greater dynamic range, and less sensitivity to environmental degradation induced by ionizing radiation.

For the past few years, the EG&G Special Measurements Photography Group, Las Vegas, Nevada, and LLNL L Division personnel have tested different photographic films to be used for data recording.

We found the Kodak T-Max 100-, 400-, and 3200-speed films to be great photographic-film advancements. These films show the first application of tabular-grain technology to black-and-white film. This film has Kodak T-Grain, an emulsion that reshapes pebble-like crystals into a slate-like, tabular form. Kodak photographic scientists have reshaped the silver halide crystals to provide more surface area to catch light. This reshaping improves sharpness, is more responsive to development changes, expands exposure latitude, and improves reciprocity with both long- and short-exposure times.

Two-Beam Nova Laser Diagnostic Equipment

One of the diagnostic equipment items that we use on the Nova laser shots is the microchannel-plate intensified grazing-incidence spectrograph (MCPIGS). The data image is emitted on P-11 phosphor, which has a spectral peak at 460 nm. Because of low- and high-intensity levels, a film with a high sensitivity at 460 nm requires a wide dynamic range. We chose the Kodak T-Max 3200 film, which can also be push-developed to a higher sensitivity. In Fig. 1, we show a scanning-electron-microscope (SEM) picture of the emulsion that we acquired by first freezing the sample and then fracturing it. This photograph shows the emulsion to be a bi-pack. A bi-pack is a combined slow and fast emulsion, with the slower grains on the bottom. It has larger, more sensitive, tabular-shaped grains on the top and smaller,

Figure 1. A cross section of Kodak T-Max 3200 film, with a 1-μm marker that shows grain size.

spherical-shaped grains on the bottom. A bi-pack emulsion gives a greater dynamic range in latitude of exposure. To calibrate the film, we filtered an EG&G MKVII xenon-flash sensitometer to simulate P-11 phosphor (Fig. 2). We then calibrated the unit at the Opto-Electronic Calibration Facility so the output appears in ergs/cm^2 . We also used a Kodak continuous wedge that is composed of M carbon. The wedge becomes spectrally flat over the visible spectrum and, thus, has a density progression of 0.30/cm over a 10-cm range. The wedge then has an exposure range of 1000:1. The duration of exposure is 10^{-3} s, which is about the decay time of P-11 phosphor. Every piece of shot film has the wedge exposed on it prior to data exposure and developing. In Fig. 3, we show the continuous wedge with alignment fiducial for digitizing. Figure 4 shows the plot of the density-vs-exposure curve.

Film images are difficult to develop evenly by hand, so we use the same type of photographic-processing machine at all locations. This machine, made by Hope Industries, Inc., is a roller transport with more than 1200 rollers. It gives constant, even agitation that results in a better processed film. The films are now digitized by an image-digitizing microdensitometer that is controlled by a microVAX computer. The digitizing-scan slit is $12.5 \times 100 \mu\text{m}$ with a pixel size of $12 \mu\text{m}$ in the x direction and $100 \mu\text{m}$ in the y direction. Data are available on LLNL's Open LabNet or can be transferred to a removable disk for data reduction. For immediate needs, a laser shot can also be quickly developed and digitized, and data can be reduced in less than 1 h.

Figure 2. Sensitometric xenon-flash and filter simulation of the spectral emission of standard phosphor P-11 (blue curve). The actual spectral emission of the phosphor (black curve) is shown for comparison.

Figure 3. Processed T-Max 3200 film that shows a continuous wedge and alignment fiducial for digitizing.

Figure 4. Density-vs-log exposure for T-Max 3200 film.

Experimental Components

Digital Data Links for Downhole Applications

N. H. Lau

Our present downhole cameras¹ consist of:

- The Reticon 100 × 100 array camera.
- The Reticon 128 × 128 array camera.
- The Fairchild 380 × 488 array camera.
- The spectroscopy array camera (SPAC) system.

Image data from these cameras are digitized, converted from parallel to serial format, and then transmitted uphole through a coaxial or optical-fiber cable to the Image Data Acquisition (IDA) system.² The Reticon cameras use coaxial cables for data transmission, with biphasic code format at 90 and 144 Mbit/s, respectively. The Fairchild and SPAC cameras use optical-fiber

cables, with nonreturn-to-zero (NRZ) code format at 180 Mbit/s. Serial data at the end of the coaxial cable, or from the optical transmitter-receiver pair over the optical-fiber cable, couple into a bit-sync module, a frame-sync module, and the memory system described below. We use dedicated bit-sync modules with each camera because of different data rates. These modules operate at a maximum data rate of 180 Mbit/s with either NRZ or biphasic format. The frame-sync module and memory system are designed to accept 8-bit data.

In addition to these imaging systems, we are developing a fast-readout Reticon camera and have in the planning phase a fast-readout Fairchild III camera. Output data

from the Reticon camera will be carried uphole through an optical-fiber cable at 90 Mbit/s NRZ. The Fairchild III camera will require a data link of 360 Mbit/s.

In this article, we describe our present data link and a second-generation data link, which we are designing for all cameras. Our plan is to replace the current 820-nm optical-fiber link with a new 1300-nm link. The bit-sync, frame-sync, and memory modules will also be re-designed to use high-speed-logic integrated circuits, programmable logic chips, and surface-mount components. The bit-sync module will accept serial data up to 800 Mbit/s; the word size of the frame-sync and memory module will be extended from 8 to 16 bits.

To preserve the high-data-rate capabilities of an optical-fiber system, we will use NRZ digital-coding format for transmission of data because bandwidth requirements are effectively one-half that of return-to-zero code format, such as biphasic. The NRZ code format will also contribute to lower bit-error rates. In conjunction with NRZ coding, we may use mBnB encoding/decoding formats, described later in this article, to further improve system reliability.

Current System

Our present digital data link consists principally of the optical-fiber link plus the uphole-storage system (Fig. 1). The optical-fiber link is composed of the optical transmitter, optical-fiber cable, and optical receiver. The uphole storage system in an IDA configuration provides data storage, which includes the bit sync,

Figure 1. First-generation, 820-nm optical-fiber data link.

frame-sync, and LeCroy, Inc., memory modules. The optical receiver and all modules in the storage system are computer-automated measurement and control (CAMAC) modules.

The bit-sync module accepts encoded serial data, locks in phase with the internal clock, and recovers a clock and data from the incoming data. The frame-sync module converts these data from serial to parallel format, checks the parity, and detects two frame-sync words. The frame-sync words and all subsequent words are then transferred to the LeCroy memory modules for storage. After an event, data can be retrieved from the input/output megadisk in the IDA system.

Optical-Fiber Transmitter and Receiver. The optical-fiber transmitter converts serial data from a camera into optical signals, then couples the signals into a fiber cable. Our current transmitter is the Optical Information System (OIS) model-OT8100 transmitter printed-circuit (PC) board. Four PC boards packaged with two dc power supplies provide redundant data channels. The OIS transmitter uses a diode laser as an optical source at 820 nm, with ~1.5-mW optical output.

We are replacing the OIS transmitter with the MA/COM, Inc., model LDT-346 transmitter. This new transmitter contains a diode laser and a thermoelectric cooler system for temperature compensation of the laser and is designed to operate at 820 nm. Two MA/COM transmitters are packaged with a single power supply to provide two data channels. A second transmitter box will provide redundancy.

The optical-fiber receiver converts the optical signal back to an electrical signal. The receiver is a discrete design using an avalanche

photodiode with an optimum wavelength of 900 nm. The design includes a dc-restoration circuit and operates at a maximum bit rate of 180 Mbit/s. The receiver is packaged in a CAMAC module but does not respond to CAMAC commands.

Bit-Sync and Frame-Sync Modules. The bit-sync module accepts data in either NRZ or biphase format; generates a clock signal, which is synchronous with the incoming encoded data; and recovers the data in phase with the clock. The clock is generated by an internal voltage-controlled crystal oscillator, which matches the data rate of the camera. Data are constrained to a fixed bit rate and bit width.

Our frame-sync module converts the serial data stream to 9-bit parallel words (8-bit data and a parity) and detects the two, consecutive frame-sync words. In the absence of frame-sync words, no data are stored in the memory module. As soon as the frame-sync words are detected, parities are checked, and all subsequent data are passed on to the memory module for storage, including the frame-sync words.

Memory System. Our commercially available LeCroy memory system consists of the controller and two memory modules. The controller receives data from the frame-sync module with the clock and stores the data in memory. Each memory consists of 64-kbit $\times$ 9-bit static, random access memory (RAM) chips with backup battery. The memory system is designed to operate in multiples of two modules. Data in the memory module can be read out on the CAMAC dataway or through an external output port. A TRAPIX system (Recognition Concepts, Inc.) is connected to the external output port for real-time display.

Second-Generation Data-Link System

We are upgrading our present data link to meet the more advanced requirements of future cameras. For the purposes of this upgrade (Fig. 2), we have established the following goals:

- All cameras will use optical-fiber cable for data transmission.
- The data link must be able to transmit data up to 800 Mbit/s.
- The data link must be able to transmit more than 8-bit data.

To convert the Reticon 100 $\times$ 100 and 128 $\times$ 128 cameras to the use of optical-fiber cables for data transmission, we want the optical transmitter and receiver to be economical. (Our current 820-nm transmitter is expensive and cannot meet high-bandwidth requirements.) The communication industry is now converging on the 1300-nm wavelength region because of lower dispersion loss and, thus, improved bandwidth performance. Two types of 1300-nm link are commercially available: a cheaper link, with a data rate of <200 Mbit/s, and a more expensive link for data rates up to 800 Mbit/s. Because our present cameras do not need a data link of more than 180 Mbit/s, we will replace the present 820-nm link with the less expensive 1300-nm link to meet our first goal. A higher-bandwidth link will be implemented at a later date, when needed.

We are evaluating the DTL-1300C transmitter (PCO, Inc.). This device uses a light-emitting diode as a light source, is sealed in a 16-pin, dual in-line package, and operates at 1300 nm over 1 km of multimode fiber of digital signals up to 220 Mbits/s. The cost of this transmitter is about 10% that of a MA/COM unit. In addition, the transmitter and its

power requirements are small enough that these units can be installed in our cameras. Two transmitters are required for each camera to provide redundancy.

The associated receiver pair of the DTL-1300 link cannot be used because the receiver circuit uses capacitive interstage coupling, which limits duty-cycle variations in serial data. Serial data of 9-bit NRZ format cannot guarantee a defined duty cycle for the receiver. An alternative is the PCO transimpedance *p-i-n* field-effect transistor (FET) receiver. This device consists of a *p-i-n* photodiode, compatible with the 200-Mbit/s transmitter bandwidth, driving a buffered output FET amplifier with dc-coupled output. The design includes a comparator and buffer following the *p-i-n* FET to operate as a digital receiver. A *p-i-n* FET receiver that operates up to

878 Mbit/s will be implemented at a later date, when such a requirement arises.

Our 8-strand optical-fiber cable (type FO-4) that is in use for the 820-nm link was neither designed nor characterized for use at 1300 nm. Nevertheless, tests have shown that its losses are 2.5 dB/km at 820 nm, and 0.7 dB/km at 1300 nm, with a bandwidth in excess of 300 MHz/km at 1300 nm. Therefore, we will continue using the FO-4 fiber cable until a higher-bandwidth link is needed.

The new bit-sync module is mainly composed of the GigaBit Logic, Inc., IC 16G041-H, which is a phase-lock-loop (PLL) clock-recovery and data-regeneration circuit for 50- to 800-Mbit/s NRZ data. The chip is both small (1.25 × 1.25 in.) and economical. Our design will include several of these modules set at 45 Mbit/s for the Reticon 100 × 100

camera, 72 Mbit/s for the Reticon 128 × 128 camera, and 180 Mbit/s for the Fairchild and SPAC cameras.

The new frame-sync module uses Sony emitter-coupled logic (ECL) chips to accept serial inputs of up to 1 Gbit/s. This module will allow us to select word size from 8 to 16 bits. The variable word size allows the system to receive 10-bit data from the Reticon 128 × 128 and Fairchild cameras, and 12-bit data from the SPAC camera. At present, the Reticon and Fairchild cameras compress 10-bit data into 8 bit for transmission. The SPAC camera separates the 12-bit word into two 8-bit words for transmission.

We will replace our LeCroy memory system with the Memory Archive Controller and Memory Archive module.³ The new controller will receive 16-bit data from the frame-sync module at a maximum rate of 100 Mword/s and pass these data to the archive module for storage. A single memory archive module contains 1 Mbyte of battery-backed memory organized as 500 kbytes × 16 bits. The system may be configured with 1, 2, 4, 8, or 16 modules. When the system is configured with two modules, the controller interleaves the data. Data in memory are read by the IDA system through the controller using the CAMAC dataway, which is limited to the CAMAC bus speed of 1 MHz.

We are studying a coding format that is an alternative to NRZ for transmitting more than 8-bit data. The PCO link can handle 8-bit NRZ data with all eight bits logic 1, or logic 0 in the worst case. When more than 8-bit NRZ data are required, most optical receivers cannot tolerate the long dc component. Thus, we are considering a new set of *mBnB* and NRZ code formats. The *mBnB* formats produce small dc components in the coded stream and

Figure 2. Second-generation, 1300-nm optical-fiber data link.

achieve a savings of the transmission bandwidth by reducing the conversion ratio of n/m , compared to the biphasic format.

Conclusions

We are phasing out our present 820-nm data-link system and stepping into the 1300-nm region by replacing the MA/COM link with the new PCO link. The advantages of this change are that all down-hole cameras will use optical-fiber cables for data transmission and will have the same type of NRZ-code format output. During the changeover, the system will continue to use the FO-4 fiber cable and the old bit-sync, frame-sync, and LeCroy memory system. Our

next step will be to replace the latter three units with new designs so that all cameras will have a common system for data transmission. When more than 200-Mbit/s data transmission is required, we will replace the PCO transmitter and FO-4 fiber cable.

Our future camera designs will include imagers of multiple outputs. The possibility of multiplexing some of these outputs will require a wide-bandwidth data link and more than 8-bit data transmission. Our second-generation data link is ready for such requirements. In addition, the second-generation data-link will offer a common data-transmission system for all present and future cameras.

Fast-Readout PINEX Camera

A. D. Conder

The pinhole neutron experiment (PINEX) is an experiment used to determine the spatial distribution of neutrons emitted from a source. Figure 1 shows a schematic diagram for a typical PINEX configuration. Neutrons emitted by the source are focused through a pinhole onto a fluor, which fluoresces when excited by an incident neutron radiation field. An image is produced on the fluor that represents the spatial distribution of the neutron flux focused upon it. The PINEX cameras take a snapshot of this image and transmit it to a remote location, where it can be stored and processed later.

PINEX cameras are used in underground nuclear tests to record certain nuclear phenomena. The use of a camera with a faster readout time could provide many benefits such as

significant cost savings per event, an increase in image resolution, and the ability to observe nuclear phenomena that are difficult to detect using the current configuration.

The fast-readout PINEX camera would allow the diagnostic canister to be shortened, bringing the PINEX module closer to the source (see Fig. 2). Because the source is a detonation, it creates a shock wave that eventually destroys the PINEX cameras. In the typical PINEX configuration, the distance between the source and the PINEX module is approximately 90 ft, which allows 3 to 5 ms before ground-shock arrival and the destruction of the PINEX cameras. In a fast-readout experiment, the distance between the source and the PINEX module would be approximately 40 ft,

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allowing only 1 to 2 ms before ground-shock arrival and the subsequent destruction of the PINEX cameras. Therefore, these cameras must be able to record and transmit their acquired image within this time frame.

Fast 100 × 100 Reticon Camera

The image-sensing device used in the fast-readout camera is the Reticon 100 × 100 photodiode array (Fig. 3). The photodiodes convert incident photons into charge. An image is simply a spatial distribution of photons. Therefore, the photodiode array can record an image as a spatial distribution of charge produced from the incident photon field. Once the image is recorded, it must be transferred from the photodiode array to

Figure 1. Schematic diagram of a typical PINEX configuration. The goal of the experiment is to measure the spatial distribution of neutrons emitted by the source.

Figure 2. (a) Current diagnostic canister showing distance from the source to the PINEX module containing the standard PINEX cameras. (b) Shortened diagnostic canister showing the approximate distance from source to the PINEX module containing the fast 100×100 PINEX cameras.

the outside world. This is done by transferring one row of stored charge at a time into a set of analog shift registers. This method is called "video flyback," a term used in the television industry. Once the charge is in, the analog shift registers it as clocked out to the analog amplifier circuitry and later digitizes it.

The fast-readout 100×100 camera can be created from a field-proven 128×128 camera (shown in Fig. 4) by making a few simple modifications. Typical PINEX experiments currently use both standard 100×100 and 128×128 PINEX cameras as shown in Fig. 4. The fast 100×100 PINEX camera is simply a modified, standard 128×128 PINEX camera.

Using the 100×100 (10,000-pixel) photodiode array in the standard 128×128 (16,384-pixel) PINEX camera allows the camera's readout time to be reduced from 2.77 ms (16,384 pixels/8-MHz clock + 128 columns $\times$ 3.3- μ s video flyback + 300- μ s exposure) to 1.88 μ s (10,000 pixels/8-MHz clock + 100 columns $\times$ 3.3- μ s video flyback + 300- μ s exposure). Readout time can be further reduced by increasing the clock rate to 10 MHz and reducing the video flyback time to 0.6 μ s, thus giving a readout time of 1.36 ms. The 300- μ s exposure time can also be reduced in some applications to achieve an even greater reduction in readout time.

The basic camera design is shown in Fig. 5. The image-sensing device is the Reticon 100×100 photodiode array (which is pin-for-pin compatible with the Reticon 128×128 photodiode array used in the standard PINEX cameras). The pixel center-to-center spacing for either photodiode array is 60 μ m.

The video information stored in each pixel is clocked out of the photodiode array at a rate of 10 MHz. The video signal is amplified,

clamped, and offset within the analog-signal processing section of the camera before being presented to the input of a 10-bit analog-to-digital (A/D) converter. The 10 bits from the converter are used to represent the analog video signal. The resulting 10-bit data word, which represents a single pixel, is then compressed to 8 bits using a look-up table stored in the firmware of the camera. After the addition of a parity bit, the data are transmitted serially from the camera to a remote high-speed memory using a digital fiber-optic link. (The fast 100×100 PINEX camera transmits data at 90 Mbit/s, and the standard 128×128 PINEX camera transmits data at 72 Mbit/s.)

Data are compressed so that the transmitted data are compatible with the remote data-acquisition equipment used in conjunction with the camera. Once acquired, the 10-bit data can be unfolded from the compressed data using a look-up table stored in computer memory. This technique imposes no more than a 0.7% error in the unfolded 10-bit data (see Fig. 6) and increases the sensitivity of the camera to low light four times, compared to an 8-bit system.

The image sensor requires various clocking waveforms produced by a single master clock that drives programmable TTL logic circuitry. To modify the clock waveforms of a standard 128×128 PINEX camera to those required by the fast 100×100 PINEX camera, we loaded a new set of firmware into the programmable logic and replaced the standard 144-MHz crystal oscillator in the master clock with a pin-compatible 180-MHz crystal oscillator.

The manufacturer of the photodiode array (EG&G Reticon) specifies a minimum flyback time for the 100×100 array at $2.5 \mu\text{s}$. To achieve a readout time of 1.36 ms, we must

Figure 3. A simplified diagram of the Reticon 100×100 photodiode array. The photodiodes are used to convert photons into charge. An image is represented by the spatial distribution of charge among the photodiodes.

Figure 4. Comparison between the standard 100×100 PINEX camera (shown on the left with camera head and controller) and the standard 128×128 PINEX camera (camera head and controller in same package), which can be modified into a fast 100×100 PINEX camera.

Figure 5. Basic block diagram of the fast 100×100 PINEX camera. (Comments within parentheses indicate hardware differences from the standard 128×128 PINEX camera.)

Figure 6. Dynamic response curve of the fast 100×100 PINEX camera viewing a flat field of uniform pulsed light at 420 nm. The 10-bit data shown were unfolded from compressed 8-bit data.

reduce the flyback time to $0.6 \mu\text{s}$. This can be done without degrading the performance of the camera because it operates in a single-shot mode. If the camera were to operate in a continuous mode, inefficiencies caused by the shortened flyback time could cause image smearing.

Conclusion

The fast 100×100 PINEX camera can be quickly and easily built up from the field-proven standard 128×128 PINEX camera and offers a small package size, low readout time, and good dynamic performance (dynamic range exceeds 100:1 in blue light). Future use of the fast 100×100 PINEX camera will depend on its vulnerability to the return-current electromagnetic pulse as well as radiation exposure when close to the source. It will be the first device of its kind to be fielded so close to the source, and many questions about its field performance in this configuration still remain.

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Generation of an Intense Fluorine K_{α} X-Ray Line for Instrument Calibrations

G. A. Burginyon, J. D. Eckels, A. J. Elsholz, and B. A. Jacoby

The calibration of instruments for spectroscopic observations of x-ray lines below 1 keV is time-consuming and difficult. In addition, few discrete x-ray lines are available below this energy. Yet, the calibrations are important in weapons diagnostics, controlled thermonuclear fusion research, and x-ray astronomy. The most convenient source of these x rays is fluoresced radiation produced by a primary x-ray-tube beam that fluoresces characteristic lines in a secondary radiator. However, the intensity of x rays from fluoresced radiation is too low (three to four orders of magnitude less than the intensity of x rays in the primary beam) for in situ calibrations of most experimental geometries.

The direct electron excitation of targets with low atomic number is an attractive alternative for generating x-ray calibration lines below 1 keV. The subkilovolt lines from these targets are K lines that are intense with simple, characteristic line spectra. In addition, the intensity of the continuum background radiation is minimized because it is proportional to atomic number. We have successfully developed such an alternative source for fluorine K_{α} (FK_{α}) x-ray lines at 676.8 eV with an intensity of more than 10^{13} x rays/s. We call it an Eckels source, after its designer. The source is mounted in a compact package that can be adapted to various experimental geometries and used

with any of the usual metallic anodes to make other calibration lines. Our focus, however, was on the source features that generate FK_{α} calibration lines at comparable intensities to metallic anodes and that last for days, giving us time to make calibration measurements.

Fluorine and its compounds cannot generally withstand the high anode temperatures generated in direct electron-excitation sources. Long-term stability and high intensity are difficult to achieve simultaneously in a practical fluorine anode because any compound of fluorine will "boil off" the anode substrate if subjected to high temperatures. This compound then coats the inside of the vacuum chamber and progressively exposes the substrate material to impinging electrons, creating a source of additional background x rays. We chose AlF_3 for the anode-coating compound and pure 1100 aluminum for the anode substrate material. The coating compound, which carries the fluorine atoms, should endure high temperatures, bond well to the substrate, and closely match the thermal properties and expansion coefficient of the substrate material. The coating compound should also have melting point, specific heat, and thermal conductivity that are as high as possible. The aluminum in the substrate material and in the flu-

orine compound has a low atomic number, which minimizes bremsstrahlung background radiation. Also, its characteristic line radiation is completely resolvable from the FK_{α} x-ray line, even at proportional-counter resolution, so that high spectral purity can be achieved in the FK_{α} line.

We optimized the design of an AlF_3 -coated aluminum anode for the Eckels source by: (1) efficiently, with water, cooling the anode to its tip; (2) vapor depositing AlF_3 on an aluminum anode-substrate material (AlF_3 bonds well to aluminum); (3) making the layer of AlF_3 as thin as possible (about 500 nm) to optimize cooling but thick enough to prevent electrons from reaching the substrate; (4) defocusing the source spot to minimize heat loading per unit area but still confining the source spot to the flat surface at the end of the anode; and (5) choosing an anode substrate whose characteristic radiation is completely resolved by a proportional counter. Then if we "burn through" the AlF_3 coating, we will not compromise the spectral purity of the FK_{α} line (95%), which is easily resolved from the AlK_{α} background line.

Typically, we operated the fluorine anode at 3.5 kV and 10 to 20 mA, which gave adequate source intensity (10^{13} FK_{α} x rays/s at 3.5 kV/15 mA) and stability for our application.

Figure 1 is a side view of the Eckels source, which emits x rays through an end and side port at 90 deg. The two ports allow us to simultaneously monitor the source strength and calibrate an instrument. The electron optics are similar to a Manson source.¹ Cooling water is brought up inside the anode to within 80 mil of the anode front surface at its closest point. Care was taken to deliver a large, continuous flow of cold water (1.89 l/min at 10°C) against the back surface of the anode to avoid bubbles and dead space. Thermodynamic calculations to model the anode configuration indicated that the temperature of the anode tip ranged from 65 to 120°C

for our operating conditions. (Arthur Sharpiro, Lawrence Livermore National Laboratory, private communication, 1989.)

We incorporated a quickly replaceable, water-cooled anode tip into the design, positioned the anode relative to the filament, and sealed it against water and vacuum leaks with a nut and a Teflon gasket that mate the anode to the water-cooling lines. To change the anode, the filament-holding cap must be removed.

Because x rays are emitted from the end and side port, electrons from the filament must be focused entirely on the flat end of the anode so the emission of the source is

the same at either exit port. We achieved this focus by adding a filament shroud, shown in Fig. 1, which extended the ground plane further up around the filament and closer to the anode. We then notched the end of the shroud so the x rays from the entire end of the anode could escape from either exit port. We operated the 12-mil, truncated-tip, tungsten-wire filament at -500-V bias and 11.5 A. A negative bias on the filament defocuses the electrons and creates a larger source spot. The source spot is in the center of the flat anode surface, shaped like a cloverleaf, and fills about half the surface of the 0.25-in.-diam anode end.

Figure 1. A side view of the compact Eckels source that emits x rays out an end and side port at 90 deg. Two ports are desirable to simultaneously monitor the source strength and calibrate an instrument.

Figure 2 shows the gradual decrease in FK_{α} line intensity as the thin coating of AlF_3 boils off the anode substrate at a constant anode current. The intensity of FK_{α} x rays typically decreases more than a factor of 2 in about 3 h. When using the Eckels source for calibrations, we usually kept the FK_{α} line intensity nearly constant by increasing anode current. At the beginning of each day, we changed to a new anode with a fresh coating of AlF_3 . This change took about 1 h but allowed us to operate at the lowest power for the same intensity of the FK_{α} line, which kept the source package from getting too hot after a few hours of continuous operation.

Figure 3 shows the x-ray spectrum from an AlF_3 -coated aluminum anode after 3 h of continuous operation at 3.5 kV/15 mA. The spectrum was recorded by a 200-Torr, propane-gas-flow proportional-counter system, registering the event through a 0.4- μ m nickel filter. The spectrum includes the FK_{α} line at 676.8 eV, which is well resolved from the AlK_{α} line at 1487 eV.

In summary, we developed an intense source of FK_{α} x rays ($>10^{13}$ x rays/s) with high spectral purity

(95%), which we can continuously operate at high power for about a day before changing the anode in a 1-h process. The Eckels source is mounted in a small package with flanged output ports so that the x rays can escape from an end or side port at 90 deg. The source is portable and, therefore, adaptable to various in situ experimental

Figure 2. Stability of source with AlF_3 evaporated on an Al anode. Variation in the intensity of the FK_{α} line vs time at constant anode parameters, 3.5 kV/15 mA, and at -500-V bias on the filament. The FK_{α} line intensity was recorded by a gas-flow proportional counter at about 33 ft from the source. Compared with previous efforts, the source intensity remains fairly constant for several hours.

geometries, particularly in applications where the source must be placed at distances >10 m from an instrument to make accurate in situ calibrations.

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Figure 3. X-ray spectrum from an AlF_3 -coated aluminum anode after 3 h of continuous operation at 3.5 kV/15 mA, registered by a 200-Torr, propane-gas-flow proportional-counter system through a 0.4- μ m nickel filter. The spectrum consists of the FK_{α} line at 676.8 eV, well resolved from the AlK_{α} line at 1487 eV. Amplitude is 4000 counts full scale. The spectral purity of the FK_{α} line is not compromised by the AlK_{α} background line.

Active Downhole Alignment-Monitoring System on the Hornitos Event

C. H. Adams, M. J. Fischer, and M. J. Doman*

We designed the active downhole alignment-monitoring system (ADAMS) on the Hornitos Event to realign the electronic pinhole neutron experiment (EL-PINEX) pinhole assembly following completion of the stemming operation. EL-PINEX is a means for obtaining

diagnostic information about the performance of a nuclear device. The performance we seek to measure is spatial information about neutron output. Neutrons released from a device during detonation are imaged by a scintillating fluor through a thick pinhole assembly in

the same way an optical pinhole camera functions. The image on the fluor is, in turn, viewed by solid-state cameras that record data and send them uphole for permanent recording. To provide the highest possible resolution of the source, cameras must view only the area

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Figure 1. Schematic of ADAMS components in the Hornitos canister package.

where the image is expected to be and not reduce the amount of alignment margin around the perimeter of the image. Thus, remote adjustment of the pinhole assembly becomes important.

Diagnostic canisters are subject to lateral displacements along their length because of the stemming process. EL-PINEX lines of sight (LOSs) are especially vulnerable to displacement because they typically run 100 ft in length, or the full length of the canister. By providing a means to realign the pinhole assembly to a previously set position, we can improve the quality of physics data. This improvement occurs by having more of the imaging pixels of the solid-state camera committed to the viewing structure of the device rather than to the misalignment margin. In other words, more of the pixels can contain data about the device, and these increases can be significant. Without an alignment system, only about 40% of the pixels yield data concerning the device. With an alignment system, up to 70% of the pixels yield data concerning the shape of the device.

The design criteria, in terms of resolution and type of misalignment, were determined by the EL-PINEX physicist (M. J. Doman, EG&G North Las Vegas Facility, private communication, 1989). Translational alignment was to be within ± 0.020 in. of the predetermined aligned position. The system was designed to allow for a possible downhole displacement of 0.500 in. at the canister midpoint. In addition, the system was designed to measure changes in tilt of the pinhole assembly with an accuracy of 0.5 mrad with respect to the EL-PINEX LOS.¹

System Description

ADAMS is composed of three different subsystems. As shown in Fig. 1, the first subsystem is a measurement system that uses two taut-wire alignment gauge (TWANG) stations. A video TWANG system includes a taut wire stretched from near the working point (WP) to near the imaging fluor of the EL-PINEX LOS. We monitored the position of the wire relative to the pinhole assembly with a compact video camera. By placing the upper and lower TWANG stations at a known distance from one another, we were able to determine the tilt of the pinhole by dividing the difference in the amount of displacement measured at each of the stations by the distance between stations. Although no corrective action could be taken, we used this information to fix any shading of the image caused by pinhole tilt.

Figure 2. Photograph of ADAMS pinhole assembly mounted on motorized x - y stages.

The second ADAMS subsystem, the actuation system, employs a computer to control the motion of the pinhole assembly, which is mounted on motorized x - y stages. In addition, we used linear potentiometers to provide motion verification.

The third ADAMS subsystem provides the ability to backfill the LOS with prestemming material after corrective motions have been completed. Backfilling is required because of the need for an open path from which radiation can flow. The ADAMS LOS is in the direct path of the imaging module in which EL-PINEX cameras are housed. If an excessive amount of a prompt radiation were allowed to scatter up the LOS, it could hinder the recording capabilities of the imaging module. Therefore, this LOS is backfilled with lead shot, which attenuates radiation. A hopper containing lead shot and a remotely controlled ball

Figure 3. Photograph of the stemming enclosure around the ADAMS motors and TWANG stations. The pinhole and stages are on the left; TWANG stations are enclosed in the box on the right.

valve accomplish this task. We use two hoppers and ball valves for redundancy. Figures 2 and 3 are photographs of ADAMS installed in the canister.

Results

ADAMS performed as expected, with no failure of components. The pinhole was translated in the x and y directions $+0.015$ and $+0.013$ in., respectively, after we observed that the alignment did not change further. The amount of pinhole tilt measured in the x direction was -0.87 mrad and in the y direction was -0.22 mrad. Our sign convention for tilt was positive when the top of the pinhole assembly tipped toward (downward to) the positive x or y axis. The final readings of the TWANG were $+0.000$ and -0.003 in. in the x and y directions. Postevent data indicated that there was no appreciable image shift at the fluor.

Figure 4. Results of the ADAMS video monitor showing the zero condition from the lower TWANG station. Each division represents 0.02 in., with $x = +0.040$ in. (left), and $y = +0.035$ in. (right).

Figure 5. Pinhole deflection vs time from the top of the hole through the first grout plug. The large change due to prestemming is attributable to the 40,000 lb of lead shot added for radiation shielding in the canister directly around the pinhole.

Figure 6. Pinhole deflection vs time during the stemming operation around the diagnostic canister. Rapid changes in pinhole deflection occurred as the hole was being stemmed past the diagnostic canister; however, after the first grout-containment plug was poured, pinhole motion ceased.

A canister bend test was performed at our Las Vegas assembly site, the EG&G Atlas Facility. The purpose of this test was to verify the capability of ADAMS by displacing the diagnostic canister in a controlled manner while it hung vertically in an alignment tower. The test showed that we were able to make the appropriate correction when the canister was displaced by a known amount (up to 0.400 in.). In addition, we found several items that required modification to allow the system to work successfully downhole. The pinhole showed no measurable tilt during the canister bend test.

Following assembly of ADAMS at the Nevada Test Site (NTS), we began nightly monitoring of the video TWANG stations to determine the zero position of the system. Our objective was to find a time when the canister neither stretched nor compressed because of thermal gradients. The canister was most stable during early morning hours; therefore, we considered the values from the video TWANG to represent the zero condition at this time. Figure 4 is a printout of the video monitor for the zero condition at the lower TWANG station.

Data from the TWANG stations as well as information from the linear potentiometers and stepper-motor position were fed into a spreadsheet, which calculated pinhole deflection and tilt. Other calculated information included the image position at the fluor and the pinhole aiming-point shift at the WP. Figure 5 shows pinhole deflection as a function of time, starting with canister prestemming, before being sent downhole. The large change due to prestemming can be attributed to the large amount (40,000 lb) of lead shot added for radiation shielding in the canister directly around the pinhole.

Figure 6 shows the amount of deflection that took place during stemming of the canister in more detail. As expected, rapid changes in pinhole deflection occurred as the hole was being stemmed past the diagnostic canister. However, by the time the first grout-containment plug was poured, pinhole motion had ceased.

When we determined that no further pinhole motion would occur because of stemming, the pinhole was moved. The amount of correction was close to the resolution limit of the video TWANG system. The

pinhole was translated in the $+x$ direction by $+0.015$ in. and in the $+y$ direction by $+0.013$ in.

Conclusions

ADAMS performed as expected in every respect. The use of stages to align the pinhole at the Atlas Facility during x-ray alignment proved to be both effective and efficient. At the same time, the stages were scribed to define the aligned position of the pinhole, which was different from the mechanical zero of the stages. This technique provided us with a verification of stage

position after shipment to the NTS. The canister bend test at Atlas was useful because it verified the potential of the system. We will apply the experienced gained in the implementation of ADAMS to improve the performance of future downhole pinhole alignment systems.

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Fabrication of Large, Layered Synthetic Microstructures with Uniform Reflectivity Performance

P. J. Bilotft and S. Falabella

Reflective optics have long been used in the visible portion of the electromagnetic spectrum of microscopes, telescopes, monochromators, and spectrometers. However, their development was delayed because the interaction of shorter-wavelength and higher-energy photons (x rays) with matter was not understood until 1912. Then in a series of experiments, the English physicists H. R. Bragg and H. L. Bragg discovered the relationship between the wavelength of incident x rays on an oriented sample of natural rock salt and the angle at which strong diffracted x-ray intensity was observed.¹ Figure 1 illustrates the phenomenon of x-ray diffraction, referred to as Bragg reflection.

For diffraction to occur, the spacing of atomic planes (or d spacing) in the diffracting crystal must be on the same size scale as the radiation

Figure 1. Bragg diffraction of light by a natural crystal. Incident photons of wavelength λ impinge on a periodic array of atoms in a natural crystal. Photons are absorbed by atoms in the lattice and re-emitted as waves in all directions, whose amplitudes add vectorially. Only waves that are in-phase produce intense diffracted beams. Bragg diffraction occurs similarly in a layered synthetic microstructure having alternating layers of high- and low-atomic-number material with a d spacing equal to the thickness of a one-layer pair.

wavelength. Natural crystals have a periodic three-dimensional arrangement of atoms that diffract x rays having wavelengths from 0.25 to 2.5 nm (Ref. 2). However, the absence of natural crystals with interatomic plane spacing appropriate for diffracting soft x rays (2 to 20 nm) continued to hamper development of diffraction-based optics even after the Braggs' discovery.³ In the 1930s, to compensate for this deficiency, scientists began to fabricate multilayered synthetic microstructures (LSMs).⁴ Improvements in thin-film deposition technology (electron-beam evaporation and magnetron sputtering) and characterization techniques (transmission-electron microscopy, soft x-ray diagnostics, and in situ deposition-rate monitors) have since helped to develop LSM fabrication.

Experimental Work

The advancing technologies of solar astronomy and plasma spectroscopy require large (10-cm-diam) and numerous optics, which are being fabricated at production facilities for thin-film devices such as the Vacuum Process Group at LLNL. In FY 1989, our goal was to mass-produce LSMs and to reduce variations in peak reflectivity and dispersion of x rays across and between their surfaces. To achieve this goal, we used a 107- × 81- × 76-cm, modular-design vacuum-process chamber. We fixed two magnetron sputter-deposition sources (carbon and tungsten) in equiradial positions, 120 deg apart, so they would sputter upward to deposit carbon and tungsten onto a rotating substrate platen. Because the sputtering efficiency of

carbon is lower than tungsten by a factor of about 10, we compensated by adjusting the source-to-substrate distances of the two sources. We used argon vapor produced from a liquid-argon dewar as the sputter-gas source to ensure purity. We controlled the following experimental variables: substrate-platen rotational velocity, sputter-gas pressure and flow (0.4 Pa and 15 standard cm³/min, respectively), and power supply to each deposition source (866 W for carbon and 319 W for tungsten). Using an iterative deposition-mask process, we improved the consistency of LSM reflectivity and resolution performance across the optic surface. The process included: (1) performing an LSM fabrication run using previously established parameters, (2) characterizing the deposition profile for both magnetron sputter sources using soft x-ray diffraction, (3) mathematically modeling the data obtained in step 2, (4) using the model to design a set of deposition masks, (5) fabricating and installing the masks, (6) performing an LSM deposition run using the redesigned deposition masks, and (7) repeating steps 2 through 6 until we achieved the desired performance uniformity. We used commercial integrated-circuit-quality silicon wafers, 10 cm in diameter and 0.5 mm thick, as substrates for LSM deposition. The crystal orientation of the wafer's surface was 111, and the nominal surface finish was approximately 0.7 nm root-mean-square.

The substrate platen's period of rotation varied between 45 and 55 s. We produced the first batch of

Figure 2. Diffraction data obtained from three locations on a multilayer LSM fabricated without deposition masking. The variations in both diffraction angle and reflectivity are unacceptably large.

multilayer LSMs using no deposition-flux masking. Results of soft x-ray diffraction analysis performed on eighteen points along two orthogonal axes across the diameter of the silicon wafer are presented in Fig. 2 and indicate unacceptably large variations in d spacing and reflectivity. We reduced these variations by changing the shape of the source aperture to compensate for a nonuniform deposition rate. We wrote a code to model the effects of these changes and to generate an aperture, or mask shape, from the system configuration and the measured deposition profiles. The code integrates the deposition profile over the path that a given point on the wafer follows across the deposition source. An automated correction algorithm in the code allows the user to interactively change the shape of the aperture opening to converge on a mask shape that minimizes thickness variations across the LSM, as shown in Fig. 3.

Model Geometry

The experimental configuration in the deposition chamber has two natural coordinate systems (Fig. 4). One is centered above the source, the other at the substrate platen's center of rotation. The deposition profile is rotationally symmetric around the center of each source so that the distance to the source center must be calculated as the substrate rotates across the source. Each source is modeled separately. Because the substrate platen rotates at a constant angular velocity, we integrated the deposition flux over this angle.

Figure 3. Plan view of deposition sources and substrate platen with masking-design coordinate system used in the computer modeling code.

Modeling the Deposition on the Wafer

The thickness of a deposited layer, T , is given by the deposition rate, D , times the exposure time, t , in the equation:

$$T = Dt. \quad (1)$$

The layer thickness is a function of distance from the platen center, R (caused by the constant rotational speed), and the deposition rate is a function of distance from the source center, r . For a substrate moving

across a nonuniform deposition source, this equation must be integrated over time:

$$T(R) = \int_0^t D(r) dt. \quad (2)$$

To integrate the equation, we must express all variables in terms of the same independent variable. The rotation angle, ϕ , is the natural choice in this case. Because the rotation speed, Ω , is constant:

$$\phi = \Omega t, dt = 1/\Omega d\phi. \quad (3)$$

The distance from the source center can be expressed in terms of ϕ . The distance the source is placed from the platen rotation center is R_0 , and the radius of interest on the platen is R :

$$r(\phi) = \sqrt{R^2 + R_0^2 - 2R_0 R \cos(\phi)}. \quad (4)$$

This equation then yields the expression for the layer thickness as a function of platen radius:

$$\begin{aligned} T(R) &= 1/\Omega - \phi(R) \int_0^{\phi(R)} D \\ &\times \left[\sqrt{R^2 + R_0^2 - 2RR_0 \cos(\phi)} \right] d\phi \\ &= 2/\Omega - \int_0^{\phi(R)} D \\ &\times \left[\sqrt{R^2 + R_0^2 - 2RR_0 \cos(\phi)} \right] d\phi, \end{aligned} \quad (5)$$

where $\phi(R)$ is the angle of the mask opening at radius R . The mask angle is specified at 20 radii to approximate a smooth curve. These integrals are performed numerically, using a fixed-step Simpson's rule algorithm. We only calculated a relative thickness across the wafer rather than the absolute thickness. Because layer thickness is directly proportional to the rotation period, we adjusted the layer thickness by varying the substrate-platen rotation time.

Figure 4. Uniformity data on d spacing for three multilayer coatings: no mask, simple masks, and computer-generated masks. The uniformity in d spacing improved from a variation of 11% (no masks) to 0.8% (computer-designed masks).

Deposition-Profile Measurement

We measured deposition rate as a function of distance from the source center by fixing a silicon-wafer substrate over each source and coating it for a specified time. We generated samples with sharply defined coated and uncoated areas and measured the resulting single layer using a

diamond stylus profilometer with an accuracy of $\pm 5\%$ in the 2- μm thickness range. We then used these data as input to the code.

Correction Algorithm

Up to this point, the code calculated the projected layer thickness for a specified mask shape. However, changing the mask angle

at 20 radial points by trial and error to achieve better than 1% uniformity in multilayer d spacing over the silicon substrate was impossible.

Therefore, we added a simple iterative routine to the code to adjust the mask shape based on the results of the previous thickness calculation. After each deposition-profile calculation, we compared the computed

Table 1. Layer thickness data for LSMs fabricated using no mask, simple masks, and computer-designed masks.

Location	No mask (Å)	Simple masks (Å)	Computer-generated masks (Å)
1	51.59	46.91	49.78
2	51.83	47.00	49.56
3	52.19	47.59	49.89
4	51.83	47.00	49.56
5	49.56	45.69	49.67
6	50.78	46.53	49.78
7	51.83	47.89	49.89
8	51.71	46.91	49.56
9	47.00	44.53	49.89
10	50.56	46.43	49.67
11	50.67	47.89	49.78
12	51.59	46.72	49.46
13	43.52	42.24	49.67
14	50.45	46.24	49.67
15	49.24	47.59	49.56
16	51.48	46.53	49.35
17	41.03	40.18	49.14
18	50.00	46.24	49.46
Minimum	41.03	40.18	49.14
Maximum	52.19	47.89	49.89
Range	11.16	7.71	0.75
Mean	49.83	46.12	49.63
Variation	0.112	0.084	0.008
Standard deviation	3.05	1.99	0.20

Table 2. Reflectivity data for LSMs fabricated using no mask, simple masks, and computer-designed masks.

Location	No mask (%)	Simple masks (%)	Computer-generated masks (%)
1	19.2	16.0	20.8
2	15.6	17.0	17.1
3	15.2	17.8	19.9
4	15.5	16.8	17.2
5	11.7	14.6	16.8
6	17.7	16.1	17.9
7	15.9	17.1	19.0
8	17.1	21.8	16.8
9	9.6	13.9	16.7
10	15.4	15.4	16.5
11	13.3	16.5	15.3
12	16.8	17.4	16.6
13	8.2	7.0	16.7
14	14.9	14.3	15.1
15	10.8	13.4	13.7
16	15.8	15.7	16.3
17	3.7	4.0	14.8
18	14.6	13.6	15.6
Minimum	3.70	4.00	13.70
Maximum	19.20	21.81	20.76
Range	15.50	17.81	7.06
Mean	13.94	14.91	16.82
Variation	0.556	0.597	0.210
Standard deviation	3.8	4.0	1.8

layer thickness at each point to the measured average thickness on the substrate and altered the mask shape appropriately. After several iterations and adjustments, we achieved the desired d -spacing uniformity. We then used the computed mask angles to generate 0.25-cm-thick stainless-steel masks using a numerically controlled laser-cutting machine.

Results

We made one LSM for each of the three techniques: no deposition masks, simple hand-calculated masks, and computer-generated masks. We analyzed these LSMs using a soft x-ray diffractometer operating with a magnesium anode cap (wavelength of photons generated from a $\text{MgK}\alpha$ transition was 0.989 nm). Results, presented in Tables 1 and 2, show 18 grid locations on each of the three LSMs. Table 1 shows layer-thickness uniformity deduced from the location of the Bragg peak maxima.

Table 2 shows peak reflectivity data for the same three LSMs. We improved multilayer d -spacing uniformity from a variation of $\pm 11\%$ to $\pm 0.5\%$ by using code-designed masks.

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High-Bandwidth Analog Measurement Technology

Theoretical Noise Sources in High-Bandwidth Analog Fiber-Optic Diagnostics Systems

K. Hagans and P. Sargis

Because the time-resolution requirements of experiments at the Nevada Test Site (NTS) exceed the capabilities of traditional electrical-analog cable, we prefer high-bandwidth analog diagnostics systems that are based on fiber-optic transmission. Although bandwidth is often our most important system criterion, nuclear signals span several orders of magnitude in amplitude, making wide dynamic range and high signal-to-noise ratios desirable characteristics of fiber-optic diagnostics systems. When designing a high-bandwidth fiber-optic link, we choose the modulator, transmission wavelength, and receiver best suited for the measurement requirements. Each choice impacts system complexity, cost, and signal fidelity.

Figure 1 shows the high-bandwidth fiber-optic systems that we have developed for the NTS in FY 1989. The first system (Fig. 1a) uses a lithium niobate Mach-Zehnder integrated-optics device as the electrical-to-optical modulator. The intensity-modulated signal is then transmitted uphole via an 810-nm single-mode fiber where it is recorded by a streak-camera receiver. We chose the operation wavelength to accommodate the photocathode sensitivity of the multichannel streak-camera receiver. The second system (Fig. 1b) exchanges the multichannel capability of the streak-camera receiver to operate in the 1300-nm, zero-dispersion region of the fiber-optic cable. This system

directly modulates a laser diode to convert the electrical signal to an intensity-modulated light signal. Uphole, the signal is received with a photodiode and then amplified to be recorded on an oscilloscope. In system three (Fig. 1c), we attempt to provide the 1300-nm system with a multichannel streak-camera capability. In this system, the oscilloscope is replaced with a streak camera and a second laser diode that operates at 810 nm.

Each system offers a substantially higher bandwidth than the electrical coaxial cable systems at a cost of

decreased dynamic range. The upper end of the dynamic range is difficult to improve. It requires changing the laser-diode structure to produce a more efficient, higher-power laser diode or redesigning the lithium niobate modulator to make it more efficient. Therefore, we chose to focus on theoretical limits of the lower end of the dynamic range (i.e., the noise floor) to identify which systems perform at their theoretical limit as well as to compare the systems. In addition, we identified which system parameters must be improved to yield the greatest performance.

Figure 1. High-bandwidth, analog fiber-optic systems: (a) 810-nm Mach-Zehnder system, (b) 1300-nm laser-diode system, and (c) 1300-nm hybrid system. We compare the noise sources for these systems in Table 1.

Sources of Noise in Each System

In each system, we consider similar sources of noise. The first noise source is optical-signal fluctuations generated by either the laser-diode modulator or the laser-diode carrier. For this analysis, we assume that no additional optical-carrier noise is induced by external reflections and that the laser is limited only by its relative intensity noise (RIN). Relative intensity noise is root-mean-square (rms) optical-power fluctuations per average power, or:

$$\frac{\langle P_{\text{rms}} \rangle}{\langle P_{\text{ave}} \rangle} \quad (1)$$

A typical laser-diode RIN is -150 dB/Hz for a laser diode operated away from its resonance peak.

The second noise source we consider is the detection-system shot noise. Shot noise arises from fluctuations in the current because of the discreteness of individual electrons. The last noise source we consider is the thermal noise in the amplification system. Thermal noise is caused by the random, thermal motion of electrons across a resistance.

Method of Analysis and Assumptions

For each system, we first calculate the gain required for a unity-gain analog link. The link loss¹ for a Mach-Zehnder link is determined by:

$$\frac{I_{\text{out}}}{I_{\text{in}}} = \frac{\alpha_m \alpha_L P_0 \gamma_0 R_s \pi}{2 V_\pi} \quad (2)$$

and for direct-modulation links by

$$\frac{I_{\text{out}}}{I_{\text{in}}} = \eta_{\text{LD}} \gamma_0 \quad (3)$$

where

α_m = modulator loss (0.25);

α_L = fiber loss (0.5);

P_0 = power into Mach-Zehnder (10 mW) and laser diode (2.5 mW);

γ_0 = detector and photocathode sensitivity (0.8 A/W and 0.02 A/W, respectively);

R_s = 50- Ω source resistance;

V_π = voltage for 100% modulation (7 V);

η_{LD} = modulation efficiency of the laser diode into the fiber (0.07 mW/mA for single-mode fiber and 0.35 mW/mA for multimode fiber).

We then calculate the noise due to the laser-diode relative intensity noise, detector-shot noise, and amplification-stage noise.

Laser noise:

$$I_{\text{RIN}}^2 = I_{\text{DC}}^2 B 10^{(G+\text{RIN})/10} \quad (4a)$$

Detector-shot noise:

$$I_{\text{SDET}}^2 = 2q I_{\text{DC}} B 10^{G/10} \quad (4b)$$

Thermal noise:

$$I_{\text{TH}}^2 = \frac{KT B 10^{(G+\text{NF})/10}}{R} \quad (4c)$$

Photocathode shot noise with an internal microchannel plate (MCP):

$$I_{\text{SMCP}}^2 = 2q I_{\text{DC}} B F 10^{G/10} \quad (5)$$

where

I_{DC} = $P_0 \gamma_0$ (direct modulation) and $0.15 P_0 \alpha_m \alpha_L \gamma_0$ (indirect modulation);

F = MCP noise factor (4);

B = bandwidth (5 GHz);

G = gain for unity-gain system;

NF = amplifier-noise figure (6 dB).

Table 1 Source and magnitude of noise in three high-bandwidth fiber-optics diagnostic systems.

Noise sources	1300-nm direct-modulation link	810-nm Mach-Zehnder link	1300-nm/810-nm hybrid link
1300-nm laser diode, I_{RIN}^2	$6.3 \times 10^{-9} \text{ A}^2$		$6.3 \times 10^{-9} \text{ A}^2$
Detector, I_{S}^2	$1.0 \times 10^{-9} \text{ A}^2$		$1.0 \times 10^{-9} \text{ A}^2$
Amplifier, I_{TH}^2	$5.0 \times 10^{-10} \text{ A}^2$		$5.0 \times 10^{-10} \text{ A}^2$
810-nm laser diode, I_{RIN}^2		$6.8 \times 10^{-9} \text{ A}^2$	$6.4 \times 10^{-10} \text{ A}^2$
Photocathode, I_{S}^2		$3.0 \times 10^{-7} \text{ A}^2$	$1.0 \times 10^{-8} \text{ A}^2$
Total, I_{N}	0.09 mA	0.55 mA	0.14 mA

In Table 1, we compare the noise floors of the three systems for a 5-GHz bandwidth. The 1300-nm direct-modulation link noise floor is dominated by the relative intensity noise of the laser. The 810-nm Mach-Zehnder link is dominated by the shot noise of the photocathode. Although a second laser-diode noise source is added to the 1300-nm/810-nm hybrid system, the total noise floor is still a factor of 4 lower than the 810-nm Mach-Zehnder system because electrical gain is added before the major streak-tube photocathode noise source. In the laboratory, we can

validate the noise-floor model for the 1300-nm laser-diode oscilloscope system by predicting 0.1 mA of noise and measuring 0.08 mA in 2.5 GHz.

Summary

We determined the theoretical noise sources in high-bandwidth analog fiber-optic links, and we developed a method to compare the noise

floor of systems based on both direct and indirect modulation. We also compared the noise floors for systems based on streak-camera receivers as well as more traditional photodiode-amplifier-based receivers. By examining the major noise sources in each link, we can optimize the dynamic range by adding gain in the appropriate places. Because we now have a

model that predicts theoretical noise performance, we can develop a plan to improve systems currently under development and to predict system performance for novel systems not currently in use.

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Large-Signal, Direct-Modulation Tests of Laser-Diode Transmitters

W. R. Woodruff and R. D. Lear

Nuclear-weapons physics research requires continual improvement in the temporal resolution of our field experiments. Experiments with temporal resolution of 100 ps or better are a frequent requirement today, and 10 ps may be required for future work. New radiation detection and measurement systems have been developed to meet these needs through the use of new technologies and through improvements in established systems.

The limiting factor in fielding such new measurements is the transmission of data away from the harsh environment of a measurement instrument, which is destroyed by the nuclear explosion, to a remote location for recording and later analysis. Coaxial cables routinely used for data transmission do not support the bandwidths required by our new instruments. Many new measurements require 1-km-long data links

with bandwidths of 3 GHz or more. Our expectation is that future experiments will require bandwidths in excess of 10 GHz.

Because coaxial-cable transmissions are limited to 500 MHz or less over these distances, we have sought to use modern laser diodes and optical fibers for high-bandwidth transmission of analog data. The high bandwidth of the optical fiber, combined with ease of application of laser-diode transmitters, makes this technique highly attractive. However, we require data links to have both high bandwidth and large dynamic range simultaneously. Some of our detection instruments have dynamic-range capabilities in excess of 10,000:1. Even when we use the maximum dynamic range of modern laser-diode transmitters, we are often required to cascade several transmitters for each instrument to meet measurement requirements.

Laser-Diode Performance

Many articles in the literature discuss problems with system response resonance resulting from relaxation oscillations in the laser diode.¹⁻⁹ Such resonance results from a cross coupling of the photon density in the laser and the laser-state population inversion. Resonances are observed when the drive current to the laser diode is changed abruptly, and they are present even for small-signal applications. A small signal implies that the modulation depth is less than 1. That is, the amount of modulation to the laser-diode bias must not exceed the continuous-wave (cw) bias level so as to minimize unwanted transient behavior due to relaxation oscillations. In fact, for best performance, a modulation depth of less than 0.7 has been suggested.⁸

When laser diodes are driven by a rapidly varying transient, they also tend to shift wavelength (or chirp)

during the pulse. Because material dispersion in an optical fiber causes different wavelengths to travel at different velocities, chirping destroys the bandwidth of the data link by spreading the pulse. Thus, we are compelled to operate near 1300 nm, where material dispersion of an optical fiber can be ignored, and pulses are not broadened.

The best economics for field applications are realized when the signal from a laser diode is recorded on a modern streak camera. Streak cameras support the high dynamic range required and allow us to record simultaneously the output from 40 to 50 fibers on a single instrument. The streak camera is read out by a large-dynamic-range, high-resolution charge-coupled device (CCD) camera.

Because available streak-camera photocathodes do not have adequate sensitivity at 1300 nm, we must convert the optical signal to an electrical signal and then back to an optical signal at 800 nm. Figure 1 shows the total field system. The complexity of this system could be greatly simplified if the streak camera were directly sensitive to 1300 nm. See the article, "Developing a New 1300-nm Infrared Photocathode for NTS Streak-Camera Applications," in this publication for details on the development of 1300-nm photocathodes.¹⁰

Large-Signal Tests

For our applications, the small-signal restriction imposes an excessive limit on the dynamic range of our data link. Therefore, we have

evaluated laser diodes for the large-signal application, where the diode is biased just above the lasing threshold. The laser is then driven by a single, short-duration pulse to positive levels above the maximum-allowed dc bias level. This application gives us maximum dynamic range while minimizing statistical error in our data.

We have tested the basic properties of our system by measuring the large-signal system-response function for the 1300-nm laser-diode/fiber-detector system. We connected the laser-diode pigtail by a welded splice to 1 km of high-quality, single-mode 1300-nm fiber, which was then spliced to the pigtail of a high-bandwidth, 1300-nm photodiode. We measured the output of the photodiode by a high-bandwidth sampling scope. Figure 2 shows our test system.

The laser diode was biased to just above the lasing threshold with a microsecond-long pulse. We tested the large-signal response of the laser diodes by adding a 60-ps positive pulse to the bias pedestal.

Figure 1. Hybrid laser-diode transmission system consisting of both 1300- and 810-nm components. This system would be greatly simplified and greatly improved by developing a high-sensitivity 1300-nm streak-camera photo-cathode.

Figure 2. Test system for the large-signal application. We used a high-bandwidth sampling scope to measure the impulse response of the laser-diode/fiber-detector system.

We varied the amplitude of the pulser and then recorded the output signal at each voltage level. The system transfer function was determined for each pulse height by dividing the Fourier spectrum of the pulser into the Fourier spectrum of the system output.

We also tested the system with a network analyzer to measure small-signal performance. In this case, we measured the transfer function by

applying a varying-frequency, bipolar, small-amplitude sinusoid to the bias voltage. The system then plotted the ratio of output to input amplitudes. This technique gives a direct measurement of frequency dependence of the transfer function for small-amplitude signals.

Figure 3 shows the results of our measurement of the system transfer function for four signals of different amplitude delivered to an Ortel high-

bandwidth laser-diode transmitter-receiver set. The transfer function has a resonance beginning at about 4 GHz and peaking at about 6 GHz. The small-signal 60-ps pulser data agree well with the small-signal network-analyzer data. These experiments also show that the resonance decreases in amplitude and moves to higher frequencies as the amplitude of the pulse is increased. We stopped our analysis at 10 GHz because of limited signal content in the driving pulse above this frequency. Figure 4 shows the frequency spectrum of the 60-ps pulser.

We also tested for repetition-rate dependence of the system by obtaining measurements at both 100 Hz

Figure 3. System transfer function for four signals of different amplitude delivered to an Ortel high-bandwidth laser-diode transmitter receiver. The system transfer function shows a broad, intensity-dependent resonance above 3 GHz.

Figure 4. Frequency spectrum of the 60-ps pulser. The pulse has little signal content beyond 10 GHz.

and 100 kHz. Figure 5 shows that the measurements are independent of the pulser repetition rate.

Conclusions and Future Directions

Our tests show that the data link described in this article performs well at and below 3 GHz. In this range, the system response function is determinable and well-behaved, and data can be transmitted without distortion. Above 3 GHz, resonances dominate the performance of the link and leads to nonlinearities. These

nonlinearities cause distortions of large-amplitude input pulses that cannot be removed in the deconvolution process because the transfer function is not unique and varies with pulse amplitude. Thus, if we want to transmit large signals, we must electronically limit the content of the input signal to no more than 3 GHz or digitally filter the resulting data to remove those frequencies above 3 GHz.

If we want to use our transmission system for frequencies above 3 GHz, we must limit the signal amplitude

to less than 1 V. For such small-amplitude signals, the system transfer function is constant enough that it can be deconvolved from the data. Under this small-amplitude restriction, we have used laser-diode systems to measure laboratory experiments up to 10 GHz.

Information in the literature suggests that performance may be improved if we pulse-bias the laser transmitter to near its saturation level, then let the transmitted signal drive the diode negatively toward its extension point.⁸ We are preparing experiments to test this mode of operation, which may extend the applicable large-signal frequency response of our device but with some reduction in dynamic range. We also plan to test new products developed by the communications industry for our specialized applications.

Figure 5. Two data sets at different repetition rates but at the same voltage. These results show that the system response function is independent of pulser repetition rate.

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High-Bandwidth, Conventional Downhole Data Systems on the Disko Elm Event

D. A. Beckedahl and J. E. Kammeraad

In FY 1989, we used conventional cable and scope systems with high-bandwidth detectors on the Disko Elm Event to provide overall system bandwidths of 1.1 GHz. We characterized the systems to 3 GHz with high accuracy to deconvolve the system response from the shot data and supply information to about 2.5 GHz with known uncertainties. This accomplishment set a new record for high bandwidth using conventional systems and required many special measurements and procedures.

Diagnostic System

Our goal was to measure the magnetic field as a function of time for numerous experiments on the Disko Elm Event with the highest bandwidth we could obtain with current technological resources. Because so many experiments required these diagnostics, it was not practical to use the high-bandwidth (multigigahertz) optical-fiber diagnostic systems that are being developed in the NTES Directorate. Instead, we optimized the bandwidth for conventional cable and oscilloscope systems by selecting high-bandwidth components wherever possible, accurately measuring the system response to high bandwidth (3 GHz), and deconvolving the system response from the event data.

A schematic of our diagnostic system is shown in Fig. 1. The derivative of the magnetic field (B), rather than the magnetic field itself, is measured by "B-dot" detectors connected to each experiment. These detectors operate on the principle of Faraday's law: The rate of change of

magnetic flux through a circuit induces a voltage in the circuit proportional to the rate of change of the magnetic flux. For our B-dot detectors, the circuit is a loop of wire. We specified the loops to be very small to obtain high bandwidth (at least 3 GHz) for the detectors. Also, we specified that the B-dot detectors produce two outputs of the same magnitude but opposite polarity (positive and negative). The two signal outputs from each detector were connected to a "balun." A balun is a high-bandwidth (well above 3 GHz) passive device that subtracts one signal from the other and thereby greatly reduces any electrical noise that the two signals may have in common. The balun removes the noise generated by radiation incident on the cables between the detector and balun.

We connected the output of each balun to an RF-19 coaxial cable, about 1100 ft long, which delivered

the signals to the diagnostic bunker. In the bunker, each cable was attached to a 12:1 equalizer, which provided uniform attenuation for all frequencies transmitted by the cables below a characteristic frequency (typically 1.3 GHz). The output of each equalizer was connected to a Barth ladder-attenuator, a high-bandwidth passive device that had several outputs with different attenuations. These outputs were recorded on KR-23GP and KR-23R oscilloscopes, which captured the signal on film. The film data were digitized after the event to produce a voltage-vs-time record.

In principle, $B(t)$ can be obtained by integrating the voltage-vs-time record by computer and scaling the result. However, the film-reading process can introduce small translational and rotational errors into the digitized data. These errors increase with time, linearly and quadratically, respectively, in the

Figure 1. Schematic diagram of a typical measurement system, using conventional cables and oscilloscopes. The two parts of the system were characterized separately.

final integrated signal. They can become unacceptably large after a few nanoseconds of data. An example of this effect is shown in Fig. 2.

Figure 2. The effect of small film-reading errors on an integrated signal. (a) A simulation of a digitized oscilloscope trace in film coordinates. (b) The effect of a +0.1 deg and a -0.1 deg rotation of the film on the voltage-vs-time record. (c) The effect of the same rotations on the integrals of the voltage-vs-time record.

To eliminate these errors, we connected one of the outputs from the ladder-attenuator to a high-bandwidth resistance-capacitance (RC) integrator, which electrically integrated the signal in real time. We recorded the result on a Tektronix 7103 oscilloscope. Because the RC integrators are passive devices, they introduce a "droop" (an exponential decay of the signal with a characteristic time constant, $\tau = RC$) into the integrated signal. We removed the effects of the droop from the digitized signal by using:

$$G(t) = F(t) + \tau^{-1} \int_0^t F(t') dt, \quad (1)$$

where $F(t)$ is the output of the integrator, $G(t)$ is the corrected integral, and τ is the time constant for the integrator (50 or 100 ns in this case).

We used the electrically integrated signal to remove the film-reading errors from the B-dot signals recorded on the higher-bandwidth KR-23 oscilloscopes. We directly compared the electrically integrated signal (corrected for droop and properly scaled) with the computer-integrated signal obtained with the oscilloscopes. The latter signal was rotated and translated until its integral agreed with the electrically integrated signal.

Figure 3. Error budget required to obtain 10% uncertainty bound at 1 GHz. Each rectangular node denotes a measurement, and each oval node denotes a process (either convolution or deconvolution). Each oval node has one output value and two input values. The output value of each process node is the quadrature sum of the two inputs to that node (i.e., $\text{output}^2 = \text{input}_1^2 + \text{input}_2^2$). The numbers given are the maximum allowable errors up to 1 GHz and scale linearly from 1 to 3 GHz. To calculate any error shown in the figure at a frequency between 1 and 3 GHz, multiply by that frequency (in GHz).

Characterization of the Diagnostic Systems

To obtain $B(f)$ to 2.5 GHz for the experiments, we had to deconvolve the impulse response of the diagnostic system from the measured signal. The impulse response for each system was obtained by convolving the responses for two halves of the system, as shown in Fig. 1. The transfer function (the Fourier transform of the impulse response) for the entire system was measured to 3 GHz, with uncertainties of less than 8.5% at 1 GHz, 17% at 2 GHz, and 25.5% at 3 GHz. These uncertainties should be interpreted as absolute upper bounds rather than as statistical uncertainties. (Thus, the uncertainty levels of 1 standard deviation would be considerably smaller than the uncertainties just stated.) With these small uncertainties in the transfer functions, we expect the transform of the final deconvolved shot data to have uncertainties of less than 10% at 1 GHz, 20% at 2 GHz, and 30% at 3 GHz.

The error budget, which provides an uncertainty bound of 10% at 1 GHz, is shown in Fig. 3. At each stage in processing the data or in characterizing the system components, a corresponding uncertainty bound must be met. For example, in the characterization of the downhole half of the diagnostic system, the transfer function must be determined to 6.7% at 1 GHz. For the uphole half of the system, the transfer function must be determined to 5.3% at 1 GHz.

To obtain accurate measurements, we used the following procedures. We characterized the downhole half of the diagnostic system (detector + balun + cable + equalizer) by connecting a step pulser with a 100-ps rise time to the downhole end of the

cable in place of the detector. This pulser has a highly repeatable output and was characterized to high accuracy (better than 2.5% at 1 GHz). We connected the output of the pulser to a special balun with very high bandwidth (8 GHz), which we, in turn, connected to the balun of the system being tested. The connection was necessary because a regular balun has two inputs of opposite polarity that must be tested simultaneously. We connected a Tektronix 7603 sampling scope at the far end of

the cable after the equalizer. The pulser was triggered 1024 times, and the average of the transmitted pulses was recorded on the sampling scope. This number of pulses was needed to reduce the effect of noise in the measurement, as shown in Fig. 4. The derivative of the input signal was deconvolved from the derivative of the recorded signal; the result was the impulse response of the test system. Because the actual system used in the experiment on the Disko Elm Event did not include the special

Figure 4. Effects of noise in the measured cable transfer functions for repeated measurements are shown for three cases. When 1024 samples were used, the results were repeatable to within the required uncertainty bounds (dashed lines).

balun, the impulse response of the special balun was also deconvolved. The result was the impulse response of the downhole half of the diagnostic system. Because the B-dot detectors had a bandwidth greater than 3 GHz, we did not include their responses in determining the system response.

To characterize the uphole half of the system (the ladder and KR-23 oscilloscopes), we also used a step

pulser and connected it to the ladder-attenuator, which was connected to the oscilloscopes. The signal recorded on each oscilloscope was digitized and processed to obtain a voltage-vs-time record. The derivative of the input signal was deconvolved from the derivative of the recorded signal to obtain the impulse response of the uphole half of the diagnostic system.

Results

The impulse response and transfer function for a typical diagnostic system used in the experiments on the Disko Elm Event are shown in Fig. 5. The 3-dB characteristic frequency is 1.1 GHz. The impulse response for each diagnostic system was deconvolved from the measured shot data, providing accurate information to 2.5 GHz (3 GHz in some cases).

This accomplishment is important for two reasons. First, we have set a new record for high bandwidth using conventional cable and oscilloscope systems. Second, the standards and procedures we used to characterize our diagnostic system can be applied to other conventional systems used in the NTES Directorate, thus providing more accurate information in many experiments.

Figure 5. (a) The impulse response and (b) the transfer function of a typical system fielded on the Disko Elm Event. Blue lines indicate the maximum error envelope for the transfer function.

Detector Development

Control, Monitoring, and Power for Active MCP-Based X-Ray Detectors

M. W. Bowers, R. J. Dell, and J. A. Rawlings

The Contact Event in June 1989 at the Nevada Test Site (NTS) required 24 new, active microchannel-plate-(MCP-) based x-ray detectors,¹ shown in Fig. 1. These active detectors, which represented a substantial increase in detectors used on any one event, contained too many channels of information for the existing field system to monitor. Therefore, we designed and built a complex active detector monitoring system (ADMS) with the capacity to monitor the more than 180 channels of data on the new active detector system. For the MCP-based detectors to detect input x-ray flux levels accurately, the ADMS must monitor MCP voltage, phosphor voltage, phosphor current, and any internal arcing of high voltage. The detectors have 36 MCPs with variable voltage from 0 to -1.1 kV and 24 phosphors with variable voltage from 0 to +20 kV, with a slow ramping from low to high voltage "ramp-up" circuit. To verify that the detectors were working both uphole and downhole, we used a dry-run system. Controlling so many detectors and monitoring more information about each than usual made the event field process one of the largest undertaken at the NTS.

Power

We purchased 20-kV power supplies that met most detector requirements and were adjustable from 0 to 20 kV with the application of a 0- to 10-V dc voltage. We also used voltage- and current-monitor outputs but had to incorporate a buffer

amplifier to make the range and output impedance of the monitors compatible with the monitor system. The buffer amplifier card checked current spikes that corresponded to arcing so that arc monitors could alert operators to detector problems.

We found a controllable MCP supply that required a 0- to 11-V dc control for an output range of 0 to 1.1 kV. The supply had an output-voltage monitor but still needed a buffer

amplifier to make it compatible with the monitor system.

Both the phosphor and MCP supplies were dc-to-dc converters. We divided the high-voltage supplies into four groups and gave each a pair of 28-V dc power supplies for redundancy. Each supply in the pair was diode-isolated from its mate and could be turned on from the diagnostics bunker, as shown in the diagnostics-canister section of Fig. 2.

Figure 1. One of the 24 new microchannel-plate detectors used on the Contact Event. This detector spatially compresses and amplifies the input x-ray image by a factor of 10,000.

Control

The ac power to the 28-V dc supplies for the high-voltage dc-to-dc converters could be controlled from either the diagnostics trailer or the control point through the timing station. After we applied power to the high-voltage supplies, we used the control voltages to bring the high-voltage outputs up to proper settings.

The high-voltage supplies had three eight-channel control units. Each channel controlled the MCP and phosphor supplies for one active detector and consisted of a pot and

ramp-up circuit for each 20-kV phosphor supply and each MCP supply. Sixteen detectors had one MCP supply each; four had two supplies; and four had three supplies.

The ramp-up circuit applied control voltage to the phosphor and MCP supplies in about 1 min. We connected the control voltages from the diagnostics trailer to the supplies in the canister via six cables with 30 conductors each and provided ac to the 28-V power supplies and the monitor system, as shown in the diagnostics-trailer section of Fig. 2.

We sent several manual and automatic signals from the control point for both the dry-run and shot configurations. We used manual signals to turn on the uphole monitor system and the ac to the 28-V power supplies, to enable the control voltage to regulate the high-voltage supplies, and to select one of two redundant downhole monitors. We sent four separate read commands to the monitor system during the last 5 min of the countdown, which initiated data storage. We sent the last data storage command at -10 s,

Figure 2. A simplified "one-line" diagram used in preparation for the Contact Event, which shows a schematic of the ADMS, the control and power system, and the dry-run system used to control and monitor the 24 detectors.

which initiated continuous logging until the event, as shown in the control-point section of Fig. 2.

Monitor

The ADMS consists of a computed-automated monitoring and control- (CAMAC-) based LSI-11/73 microcomputer-system master crate and two redundant remote-slave CAMAC crates (Fig. 3). We placed the master crate in the high-voltage and vacuum trailer in the recording trailer park with the two remote-slave CAMAC crates mounted on the downhole experimental canister (Fig. 4). The system used a separate CAMAC serial highway to communicate with each downhole crate for fault tolerance, and the serial highway used standard CAMAC modules. For noise suppression, we added an unbalanced, terminated 50- Ω coaxial cable instead of a balanced, 100- Ω transmission line. The master crate controlled the downhole crates, monitored the vacuum-pump power supplies required for the 24 detectors, and provided two serial links to the control-point complex for real-time monitoring of the experiments. The links were connected through a terminal multiplexer system and the user-encoder system via a microwave. The master crate monitored timing and control signals sent from the control point. These signals selected the downhole crates for data acquisition. Other signals directed the system to store current-detector measurements in a nonvolatile memory for later analyses.

The software was written in Oregon Software's Pascal to run under Digital's RT-11 operating system. The 8000 lines of code initialized the CAMAC crates, read the raw data from the downhole crates, corrected them for deviations, and displayed the data on any remote

terminal. A data base drove the configuration for this event. Because the software is copious and complex, we had to break the code into smaller subsections with overlays. For future events, we will eliminate the

need for overlays by using a multi-tasking operating system. We analyzed the monitored data on a VAX mainframe nonvolatile memory at the control point after each dry-run event and after the Contact Event.

Figure 3. The master uphole-controlling CAMAC crate. This crate uses many commercially available modules and only two LLNL-designed modules, which makes the system easy to design and build.

Dry-Run Testing

We tested 20 of the 24 active detectors by incorporating a dry-run system into the ADMS. This system consists of a nitrogen laser, 20 ultraviolet fibers, and 20 fiber-optic switches. The laser transmits 337.1-nm light through low-loss ultraviolet fiber (>2 dB/m) to the detector. The detectors are barely sensitive to this wavelength; therefore, we could only test them at higher gains than the event settings. Because we could not

establish in advance what the fluorescence of the fibers would be during event radiation, we installed a fiber-optic shutter switch for each of the 20 detectors using the dry-run system. As zero time approached, the dry-run system gave us confidence that the detectors were still operating.

Results

We successfully fielded the ADMS on the Contact Event in June 1989. The system helped us diagnose an

arcing problem with two detectors, allowing us to reduce their voltage before detector data were jeopardized. In fact, the system provided valuable and accurate information about all 24 detectors by monitoring voltages to better than 1%, low-level currents, and low levels of arcing.

We are upgrading this large, flexible system to field on future events by modifying portions of the ADMS to make it a multitasking system. The upgrade will expand the number of channels we can monitor by at least a factor of 4. We may replace the numerous multiconductor cables that control the downhole power supplies with controller boards in the downhole CAMAC. Because each board will control multiple detectors, the system must be redundant. The CAMAC system will eliminate many cables but introduce additional possibilities for detector failure because integrated circuits have a higher failure rate than hard-wired circuits.

Figure 4. The ADMS acquires data with one of two redundant downhole crates and sends it to the contact point. This system has the capacity to monitor more channels of information than have been monitored on previous events.

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Diamond Photoconductive Detector

C. L. Wang, J. L. Gaines, J. E. Flatley, J. R. Hunter, and B. A. Davis*

Both semiconducting^{1,2} and insulating diamonds^{3,4} have been investigated as picosecond optoelectronic switches. The former yielded response times of 50 to 300 ps, while the latter provided 150-ps resolution. More recently, insulating diamond has been used as a sub-nanosecond x-ray calorimeter for the study of laser-produced plasmas.⁵ Because of its large bandgap (5.47 eV at 300 K), the diamond photoconductive detector may offer a significant advantage over GaAs and InP photoconductors, which have narrower bandgaps and, typically, a large, dark current ($\sim 1 \mu\text{A}$). Therefore, the sensitivity of these detectors cannot be calibrated with the dc x-ray machine or gamma-ray source but must be cross-calibrated with pulsed sources against a reference detector that can be dc calibrated. By eliminating the tedium and susceptibility to large errors associated with calibrating such detectors, the diamond detector has obvious potential value as a fast x-ray and gamma-ray detector for Nevada Test Site (NTS) applications.

This project is designed (1) to take advantage of the large bandgap—and hence, small, dark current—of the insulating diamond detector and demonstrate the feasibility of its dc calibration, both with a ^{60}Co gamma-ray source and with low-energy x-ray machines; and (2) to measure the spectral response of the diamond detector and assess its validity as an x-ray calorimeter.

Insulating Diamond Photoconductive Detectors

Our diamond detectors are made with natural, single-crystal insulating diamond (type IIa) of three sizes: $1 \times 1 \times 1 \text{ mm}^3$, $1 \times 1 \times 2 \text{ mm}^3$, and $1 \times 1 \times 3 \text{ mm}^3$. Two opposite $1 \times 1 \text{ mm}^2$ surfaces are metalized with gold to provide ohmic contact and serve as electrodes. The gap lengths (1, 2, and 3 mm) will be suitable for our future study of detector linearity as a function of bias voltage.

Detectors for gamma-ray calibration with the cobalt source are mounted inside a thin brass container filled with oil to prevent any space-charge effect resulting from

contact with air. Detectors for x-ray applications are simply mounted on commercial (SMA) high-bandwidth connectors.

Temporal Response

The time resolution of our diamond detectors was measured with 50-ps, 16-MeV electron pulses at the EG&G linear accelerator (linac) in Santa Barbara. The detector signals were recorded with a 20-GHz sampling oscilloscope averaging 20 linac pulses. An example of the impulse response of the $1 \times 1 \times 2 \text{ mm}^3$ diamond detector with its integrated signal is shown in Fig. 1. The remarkably little tail seen with this detector contrasts sharply with the long tails from GaAs or InP detectors, which require irradiation of $\sim 10^{15}$ 14-MeV neutrons/ cm^2 to eliminate.⁶ Although our diamond detectors clearly show good time resolution without neutron

Figure 1. The temporal response of a $1 \times 1 \times 2 \text{ mm}^3$ diamond detector to 50-ps, 16-MeV electron pulses. The observed impulse response is 159 ps.

Figure 2. The response of a $1 \times 1 \times 1 \text{ mm}^3$ diamond detector to x rays generated by a 120-ps, 1.06- μm , 2.5-J laser irradiating a uranium disk target at $2 \times 10^{15} \text{ W/cm}^2$.

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treatment, we found that impulse responses of the detectors we tested ranged from 160 to 380 ps. We attribute this rather large variation to irregularities in impurity concentration in the natural diamond.

For practical application in the laboratory, we installed a $1 \times 1 \times 1$ -mm³ detector on the Janus target chamber as a fast x-ray calorimeter. The detector was biased at 500 V and was placed 17 cm from a uranium disk target. The 120-ps, 1.06- μ m laser was operated at 2.5 J and was focused on the target to yield 2×10^{15} W/cm². The signal was recorded on a 1-GHz oscilloscope. The trace shown in Fig. 2 illustrates the speed and sensitivity of the detector; we are investigating whether it is a good x-ray calorimeter.

dc Calibration of Diamond Detectors

We can now take advantage of the large bandgap of the diamond detector to demonstrate the feasibility of

its dc calibration. We first attempted our dc calibration using the intense ⁶⁰Co gamma-ray source at the Las Vegas facility of EG&G. Indeed, we found the dark current of the diamond detector to be quite low ($\sim 10^{-12}$ A) and the signal to be at least an order of magnitude higher. However, we noted that the space charge generated by contact with the air gave rise to spurious signals. This problem was solved by mounting the diamond chip inside a thin brass container filled with oil. Figure 3 shows the measured sensitivity for $1 \times 1 \times 2$ -mm³ and $1 \times 1 \times 3$ -mm³ detectors as a function of bias voltage.

Encouraged by our success with the ⁶⁰Co source, we continued our dc calibration with the low-energy x-ray machine (LEX) and found that the signal was almost an order of magnitude higher than the dark current. Figure 4 shows the measured sensitivities of a $1 \times 1 \times 1$ -mm³ diamond detector to x rays of 1.5, 2, and 3 keV for bias voltages of 524 and 824 V.

Figure 3. Measured sensitivity of $1 \times 1 \times 2$ -mm³ and $1 \times 1 \times 3$ -mm³ diamond detectors to ⁶⁰Co gamma rays as a function of bias voltage.

Discussion

We have confirmed that insulating diamond is a good, fast radiation detector with a time resolution of

Figure 4. Measured sensitivity of the $1 \times 1 \times 1$ -mm³ diamond detector to x rays of 1.5, 2, and 3 keV for bias voltages of 524 and 824 V.

~ 150 ps. For the first time, we have shown that the diamond detector can be calibrated with either a dc gamma-ray or x-ray source. These reliable and easily performed calibrations indicate a great potential for diamond detectors in NTS applications. In view of the discrepancies between the field data and the pulsed laboratory calibration of the GaAs detectors, it is particularly crucial to investigate whether the dc-calibrated diamond detector may provide improved results for the NTS gamma-ray measurements. Furthermore, the diamond appears to be several times more sensitive than the GaAs detector and may prove to be an important detector for the NTS x-ray measurements when coupled with the dc calibration.

With respect to the diamond's spectral response to x rays, our limited data suggest a flat response up to 2 keV only. We plan to extend the data up to 8 keV and below 1 keV when time becomes available on the the ion-accelerator, subkilo-volt x-ray machine.

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Developing a 1300-nm Infrared Photocathode for NTS Streak-Camera Applications

R. D. Lear and C. L. Wang

Refined and improved nuclear weapons require improved temporal resolutions from the field systems that detect and measure the radiation produced in a nuclear explosion. Today, equipment with a temporal resolution of 100 ps or less is a common requirement of the system, and 10 ps is expected in the future. We are working on the problem of how to transmit and record these improved temporal resolutions.

First, the data must be transmitted away from the instrument, which is destroyed in the nuclear explosion, to a remote area for storage and analysis. When transmitted more than 1 km, many of the signals require bandwidths of 3 GHz or greater. We expect future field systems to require bandwidths in excess of 10 GHz. We have found that electro-optic transducers and long-distance, single-mode, fiber-optic cables can transmit these high-bandwidth signals. The cables perform at maximum bandwidth and with minimum loss at 1300 nm because material dispersion in the glass-fiber cable, which occurs when different wavelengths travel at slightly different velocities, is nearly zero. These 1300-nm cables can easily transmit 10-GHz data more than 1 km.

Many of the products that we use to transmit data were developed for the telecommunications industry. New 1300-nm laser diodes can transmit 3- to 4-GHz bandwidths for large signals and 10 GHz for small signals. Optical modulators, devices that vary the intensity of a "carrier" light beam in response to the applied signal, are available at 2 to 3 GHz.

Modulators beyond 10 GHz are being developed.

Although we have the technology to transmit high-bandwidth signals, recording them presents a problem. Modern oscilloscopes can record up to 6 GHz, but they are expensive and can record only one channel of data per instrument. Streak-camera systems can record many channels of data per instrument and at the required high bandwidths. However, the current systems do not have photocathodes with adequate sensitivity at 1300 nm (Fig. 1).

The solution is to improve our existing streak-camera systems so we can take full advantage of our ability to transmit bandwidths in excess of 10 GHz. Therefore, we are developing a new high-performance photocathode for our streak-camera systems that will allow us to record high-bandwidth signals at 1300 nm. The minimum performance characteristics desired are shown in Table 1. After reviewing the literature and exploring all possible technologies, we elected to develop a photocathode that is based on recent developments

Figure 1. Sensitivities of various photocathodes. Current photocathode sensitivities are not adequate in the region of 1300 to 1600 nm.

Table 1. Comparison of desired and expected performance characteristics for a 1300-nm photocathode.

	Desired performance	Expected performance
Quantum efficiency	>1% at 1300 nm	~10% at 1300 nm
Impulse response	≤30 ps (FWHM)	~12 ps (FWHM)
Dark current	≤10 ⁻⁶ A/cm ²	~5 × 10 ⁻⁷ A/cm ² thermal electron at 300 K <10 ⁻⁷ A/cm ² from hot holes injected into emitter at 300 K
Spatial resolution	≤100 μm	8 μm
Minimum active area	20 × 1 mm	Mosaic required
Photocathode life	<ul style="list-style-type: none"> • 1-y shelf life • Several hundred hours under applied bias • Hours of optical illumination 	To be determined

Figure 2. Our complete measurement system includes high-bandwidth detector, optical transmitter, optical fiber, and streak-camera recording system.

Figure 3. Schematic energy-band profile of the proposed new photocathode material. The bandgap energy of the central $p\text{-In}_x\text{Ga}_{1-x}\text{As}$ or $p\text{-In}_x\text{Ga}_{1-x}\text{AsP}$ region is adjusted to absorb 1300-nm photons (0.95 eV).

in field-assisted semiconductor materials.¹⁻³ The expected performance for this photocathode is also shown in Table 1. We are negotiating a contract with an outside vendor to develop this specialized photocathode material and to implement it in a modern streak-tube design.

Our preferred system is shown in Fig. 2. Output from a high-bandwidth radiation detector is split to drive multiple 1300-nm transmitters. The signal amplitude to each transmitter is adjusted to increase the overall dynamic range of the measurement instrument. An output signal from each 1300-nm transmitter is relayed uphole on a 1300-nm single-mode optical fiber to an infrared-sensitive streak camera. Our total recording system consists of the streak camera, an image intensifier to amplify and relay the image, a digital solid-state video camera, a control computer, and a battery-operated memory. Each streak-camera system can record the output from 40 fiber channels.

Photocathode Material

The proposal for the photocathode material is based on the research of Bell, Escher, and their coworkers.¹⁻³ A schematic of the band profile for the proposed material is shown in Fig. 3. An absorption layer of either $p\text{-In}_x\text{Ga}_{1-x}\text{As}$ or $p\text{-In}_x\text{Ga}_{1-x}\text{AsP}$ is lattice-matched to a high-purity $p\text{-InP}$ single-crystal wafer. Next, a lattice-matched $p\text{-InP}$ surface protection layer is grown over the absorption layer. Finally, silver and Cs_2O are applied to the InP protection layer to reduce the work function of the material, thus allowing electrons to escape from the surface.

The 1.35-eV bandgap of the InP is greater than the 0.95-eV energy of a 1300-nm photon. This prevents electrons from being excited to the conduction band in the InP regions

of the photocathode when exposed to 1300-nm light. However, the bandgap of the absorption layer can be adjusted to slightly less than the photon energy by adjusting the ratio of the In and Ga. This allows 1300-nm photons to promote electrons to the conduction band in the absorption layer.

However, the conduction electrons produced in the absorption region see a potential energy "hill" as they diffuse outward and, consequently, are unable to reach the vacuum surface. Applying a negative bias of a few volts can bend the band structure and remove the hill. The results of calculations on the bending of the lowest-energy conduction band (Γ band) with applied voltage are shown in Fig. 4 (Ref. 3). At an applied bias of -3 V, the conduction band decreases monotonically all the way to the surface, and electrons can then reach the photocathode-vacuum interface.

A schematic of the band profile for the biased material is shown in Fig. 5. Although the Γ band approaches the vacuum surface as a monotonically decreasing function, the surface work function is high, and the Γ band energy is still below the vacuum level so that electrons cannot escape the surface. However, as the electrons move to the surface under the influence of the applied voltage, their energy increases as they are "heated" by the applied voltage. Some of them are transferred to the next-highest-energy conduction band (L band), which is above the vacuum level. These L-band conduction electrons can then escape the vacuum surface to become "photoelectrons." The results of conduction-band population calculations by Escher and coworkers³ are shown in Fig. 6. With an applied voltage of -3 V, which gives field strengths of 10^4 V/cm

within the material, a Ag/ p -InP emitter surface has about 70% of its conduction electrons in the higher-energy L band.

Thus, as 1300-nm photons are incident upon the InP substrate (left side in Fig. 3), the region is transparent to them because of its large bandgap energy. The photons pass through to the absorption region, where they are

absorbed in the narrower bandgap material, and produce conduction electrons. These conduction electrons are then forced to the vacuum surface and elevated from the Γ band to the higher-energy L band by the applied voltage. At the surface, they can escape to the vacuum as a result of the reduced work function of the surface materials.

Figure 4. Calculated conduction-band profiles as a function of bias voltage. At -3 V, the band structure is monotonically decreasing to the surface, which allows conduction electrons to reach the photocathode-vacuum interface.

Figure 5. Schematic of the energy-band profile under bias. The Γ band is still below the vacuum level at the surface. Conduction electrons are elevated to the L band, which is above the vacuum level, allowing them to escape from the surface.

Projected Photocathode Performance

Experiments by Escher and coworkers provide us with preliminary performance parameters of the photocathode.³ They measured the reflection-mode quantum efficiency

for a Ag/*p*-InP/*p*-In_{0.53}Ga_{0.47}As cathode. Such measurements illuminate the photocathode on the same side as the photoemission. Their results, shown in Fig. 7, indicate that 1300-nm quantum efficiencies of greater than 1% can be

obtained. Even higher quantum efficiencies are reported with 8% achieved at 1550 nm.

We require a transmission-mode photocathode for our applications. Transmission mode means that the photocathode is illuminated from the side opposite the photoemission direction. In this case, antireflection coatings applied to the InP substrate will further enhance the photocathode quantum efficiency by passing more of the incident photons to the absorption region. We expect to achieve quantum efficiencies of greater than 10% at 1300 nm.

Escher and coworkers³ also discuss dark current as a function of applied bias voltage for a Ag/*p*-InP cathode. They report dark-current densities of less than 10⁻⁷ A/cm² at room temperature from a photocathode built for high sensitivity at 1400 nm. A photocathode tuned to 1300 nm should be even less sensitive to thermal noise. Dark current can be lowered still further by cooling the photocathode.

We can expect spatial resolution at about 8 μm and a temporal impulse response of about 12 ps (V. Aebi and R. Bell, Varian Corp., Palo Alto, California, private communication, 1989). The lifetime of the photocathode is still unknown because there are no data on the performance of these materials in a sealed vacuum tube—all existing data are for actively pumped experimental stations. The initial phases of the development contract will focus on determining the expected lifetime of the photocathode using accelerated lifetime studies.

Conclusions

The projected performance characteristics of this material are very promising. We expect to meet or exceed all of the requirements for

Figure 6. Calculated conduction-band populations as a function of applied bias voltage. At -3 V, about 70% of the conduction electrons are in the L band.

Figure 7. Reflection-mode quantum efficiencies for a Ag/*p*-InP/*p*-In_{0.53}Ga_{0.47}As photocathode. Quantum efficiencies of >1% are seen at 1300 nm.

field applications. With this photocathode, we can take advantage of new developments in the telecommunications industry to achieve high bandwidth (~ 10 GHz) and high density (~ 40 channels/streak camera) at potentially less cost.

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Microchannel-Plate-Intensified, Subnanosecond X-Ray Imaging Camera

M. R. Carter, B. J. McKinley, and K. G. Tirsell

We have developed a microchannel-plate- (MCP-) intensified, subnanosecond x-ray detector with 400-ps time resolution and 180- μm spatial resolution. This device enhances our capabilities for one-dimensional imaging and spectroscopic measurements of x-ray emission from laser-produced plasmas.

Figure 1 shows our x-ray imaging detector. This system consists of an ultraviolet (UV) prefilter, an x-ray photocathode (CsI, CuI, or gold) that is deposited on the MCP to enhance efficiency, focusing electrodes, a fast phosphor, and an optical-fiber faceplate for transmitting light out of vacuum. Focusing electrodes compress the electron current out of the MCP in one dimension, thereby enhancing the system gain by a factor of 10. The In:CdS phosphor-coated optical-fiber faceplate is biased up to +20 kV to attract electrons exiting the MCP. Gains of greater than 1000 can be obtained from the MCP, depending on the bias voltage. The CsI detector is about six times more sensitive than the CuI detector at 700 eV, consistent with photocathode-response data.¹

We measured the relative spectral response of CuI and CsI detectors at the Stanford Synchrotron Radiation Laboratory (SSRL) beamline 8-2 from 450 to 1300 eV, with the beam

incident on each detector at 35 deg from normal.² The detector was positioned so that the entire 2- $\times$ 20-mm beam fell on the MCP stripline. We measured the incident x-ray flux with

Figure 1. Schematic of the MCP-intensified x-ray detector system. An x-ray photocathode consisting of CsI, CuI, or gold is deposited on the MCP to enhance efficiency. The focusing electrode compresses the electron current in one dimension, enhancing system gain. The optical-fiber faceplate is biased up to +20 kV to attract exiting electrons.

a calibrated gold-mesh monitor and recorded the detector output with a Reticon camera.

Figure 2 shows the results of our measurements. The difference in MCP bias voltages, the measured transmission of the aluminum UV light shield, and the response of the gold-mesh monitor have all been

considered. We calibrated each photocathode using three different pre-filters (iron, copper, and magnesium) to reduce higher-order and specularly reflected photons exiting the monochromator. Data taken with the copper and magnesium prefilters agree well in their region of overlap for both CuI and CsI and are shown

in Fig. 2 as one curve. Data taken with the iron prefilter are significantly higher than the copper pre-filter data in the region of overlap. This result is not well understood at present. The CsI data show a strong increase in sensitivity at the Cs M_5 edge (726 eV) and at the I $M_{4,5}$ edge (630 eV). The CuI MCP response increases at the Cu L_3 edge (932 eV) and at the I $M_{4,5}$ edge (630 eV). The Cu-edge jump is much smaller in magnitude than that determined from photoabsorption cross-section [$E\mu(E)$] data.¹ Another significant difference between our measured response and a simple $E\mu(E)$ model is the gradual rise in efficiency above the Cs edge for CsI and above the I edge for CuI. These deviations from theory are not understood as yet.

In summary, we have developed an x-ray imaging detector with sub-nanosecond time response, high efficiency, and good spatial resolution. We have measured the response to x rays from 450 to 1300 eV. This detector has led to dramatic improvements in our ability to diagnose high-energy density experiments.

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Figure 2. Relative responses of CuI- and CsI-coated MCP imaging detectors vs x-ray energy. The vertical scale is in units of watts out per x-ray watts incident.

A Passive, 100-ps, X-Ray-Driven Pulser for Gating Microchannel-Plate Detectors

A. R. Fry and P. T. Springer

Microchannel plates (MCP) used in x-ray detectors have increased the sensitivity of x-ray spectrometers to small signals.¹ In addition, MCPs can make precise temporal discriminations when used in a pulse-biased strip-line configuration.¹ An MCP is an active electron-gain device consisting of millions of channels bored into a glass plate with ohmic contacts on both sides. A bias voltage is applied across the plate, which accelerates electrons in the channels, creating multiple secondary electrons. This cascading effect results in gains from 1000 to 10,000, depending on the bias voltage. X-ray signals arriving before and after the biasing period of the MCP are reduced in intensity by several orders of magnitude compared with those arriving during the biasing period. Therefore, it is best to deliver a square-wave pulse of high voltage to the MCP, accurately synchronized with the arrival of the x-ray signal of interest. We have demonstrated the feasibility of using a passive, dc-biased, x-ray-driven pulser with a 100-ps rise time to gate MCPs in downhole experiments and have eliminated the need for external timing fiducials and pulse-biasing electronics.

Auston Switches in Laboratory Experiments

In laboratory experiments, pulse biasing of MCPs is achieved by using Auston switches and pulse-biasing electronics.¹ An Auston switch is a photoconductive semiconductor with two ohmic contacts.² Freed by photoelectric conversion of light, carriers conduct current across the gap between these two

contacts. Many carriers can be generated quickly by a short, intense laser pulse that rapidly closes the switch between the contacts. In this state, the switch is an electrical short at low voltages.³ When the illumination stops, the conductivity decreases at a rate determined by the carrier recombination rate until it reaches the dark level of the thermal generation of the carriers.

In laboratory experiments, such as those at the Nova laser, Auston switches are used with x-ray detectors and are triggered externally by short laser pulses that are synchronized to activate them at shot time. Special high-voltage, fast-gating circuitry developed at LLNL provides the electrical biasing to the Auston switch at the time of the laser shot. An electrical pulser is used because the silicon photodiodes for these experiments have relatively slow carrier-recombination rates (about 100 μ s) and cannot electrically isolate a high enough dc voltage to provide gain in the MCPs. The laser-pulsed Auston switch gates voltage to the MCP for much shorter times (500 ps) than pulse-biasing electronics.

Downhole Environment

No system exists for using lasers to externally trigger Auston switches or for electrically triggering pulse-biasing networks in downhole experiments. Furthermore, the additional hardware required and the timing considerations make development of such a system impractical. The use of time-discriminate spectroscopy is, however, desirable to characterize time-specific spectra.

To benefit from the application of Auston switches in downhole experiments, we changed two critical components of the pulser: (1) the method of biasing, and (2) the means of triggering the switch. Rather than use pulse-biasing electronics, we chose a dc-biased scheme. Instead of relying on external triggering, we investigated triggering the switch with x-ray photons from the same source as that observed by the detector. This triggering scheme has three requisites: (1) the Auston switch must be able to electrically isolate a high enough voltage to bias an MCP, (2) the Auston switch must be switched with x rays, and (3) a geometry must be imposed on the detector to record the signal that is biasing the MCP.

Switch Design

Our prototype x-ray-driven pulser using a GaAs Auston switch is shown in Fig. 1. We mounted the Auston switch onto a dielectric board with a bottom ground plane between two copper strip lines that are also mounted to the dielectric. The characteristic impedance of the strip line is determined by:

$$Z_0 = \left[102\pi / (\epsilon_{\text{eff}})^{0.5} \right] + \left[\frac{w}{h} + 1.393 + 0.667 \ln \left(\frac{w}{h} + 1.444 \right) \right], \quad (1)$$

where

$$\epsilon_{\text{eff}} \approx \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \times \left(1 + \frac{12h}{w} \right)^{-0.5}. \quad (2)$$

In Eqs. (1) and (2), Z_0 is the impedance of the strip line, ϵ_{eff} is the effective dielectric constant, ϵ_r is the dielectric constant, w is the width of the strip line, and h is the height between the strip line and the ground plane.⁴ The Auston switch is glued with silver conductive epoxy to create ohmic contact with the strips. In our tests, we tailored the width of our strip lines to achieve 50- Ω impedance, which we tested with time-domain reflectometry. In principle, any impedance can be obtained by solving these equations.

One side of the GaAs strip line is biased by a resistor with a capacitor to ground and stores the charge that will bias the MCP. The amount of charge stored in the charge line is proportional to the length of the strip line. Therefore, the MCP will be biased for a time that will be equal to half the length of the charge line divided by the speed of a transverse-electric-mode wave on the charge line (the speed of light divided by the square root of the dielectric constant). For most tests, we used a length that gave a 500-ps charge pulse.

The strip line on the unbiased side of the GaAs chip connects to the impedance-matched strip lines on the MCP. For our calibration

experiments, we simply soldered an electrical connector to the strip line, which we then attenuated and read into a digitizing oscilloscope to record the pulse shape.

In an underground nuclear test, gamma rays or neutrons may pretrigger the prototype pulser before the detector can record the event. Therefore, we must choose the resistor and capacitor values on the bias side so that the resistance-capacitance time constant is slow enough to prevent constant discharge but fast enough to recharge the strip line before the photons from the source under examination arrive.

The configuration shown in Fig. 1 is a turn-on configuration in which the MCP is not biased until x rays trigger the switch. The pulser can be adapted to a turn-off configuration by placing the Auston switch between the strip line and ground, while keeping the strip at constant voltage. With the turn-off configuration, the ground pulse is timed to gate off the bias to the MCP after the x rays of interest have been recorded. This configuration is typically used in laboratory experiments.

We chose GaAs chips for our Auston switches because of their high resistivity ($10^8 \Omega\cdot\text{cm}$) and

sensitivity to x rays.⁵ We performed several experiments and found that a 1-mm-thick GaAs switch with a 3-mm gap between ohmic contacts could electrically isolate a dc bias as high as 5.7 kV in room light. When shielded from light, it could isolate up to 7 kV, permitting less than 2 mA of current leakage. Visible light (1.7 to 3.1 eV) is sufficient to free charge carriers to conduct current across the 1.4-eV gap in a GaAs chip from the valence band to the conduction band.

If the photon energy exceeds the threshold for photoconduction by an amount greater than the thermal energy (kT), the excess energy is imparted to the electron-hole pair in the form of kinetic energy. A significant fraction of this excess energy will be lost to the lattice because of various scattering mechanisms. Therefore, the energy required to create an electron-hole pair, (E_n), with 1-keV x rays is about 5 eV (Ref. 5). Using this factor and the carrier mobility (μ) in GaAs ($8000 \text{ cm}^2/\text{V}\cdot\text{s}$ at 2-kV bias),⁵ we determine an expression for Q , the necessary x-ray flux to open the switch.

$$Q = \frac{gE_n}{ewR\mu} \quad (3)$$

where g is the length of the gap between the terminals of the Auston switch, e is the charge of the electron, w is the width of the Auston switch, and R is the resistance of the Auston switch. For reasonable voltage-pulse transmission across the switch, R must be small compared with the characteristic strip-line impedance. Using the parameters of our prototype switch, we applied Eq. (3) and found that the x-ray flux must be about $3 \text{ mJ}/\text{cm}^2$ to bring the resistance down to 0.1Ω .

The x-ray-driven pulser uses the unterminated strip-line geometry in

Figure 1. Prototype passive GaAs-based pulser. The GaAs chip is mounted on a dielectric board between impedance-matched strip lines. X rays create photoconductive currents in the chip, which opens to bias the microchannel plate.

which only half the applied voltage, at most, can be transferred to the MCP through the Auston switch. When the Auston switch is opened, the distribution of charge on the strip line is identical to the superposition of two current waves traveling in opposite directions, each with an amplitude of half the bias voltage. Therefore, the wave transmitted through the Auston switch is twice the temporal length of the strip line and has an amplitude of half the bias voltage (charge is conserved). For most MCP applications, typical bias requirements are between 700 and 1200 V (Ref. 3). The switches we tested will electrically isolate twice this voltage range easily with little current leakage.

Calibration

To demonstrate that the prototype pulser could deliver voltage to an MCP, we biased it to 2500 V and shot it for about 1 ns with about 5 mJ of green- (530-nm) light pulse from the Janus laser. The output was attenuated and recorded into a Tektronix 7250 digital oscilloscope. Figure 2 shows the scope trace of one of these shots. The high tail on the trace was caused by residual resistance in the signal path of the prototype switch. This mismatching was caused by rough solder joints, conductive epoxy joints, the ohmic plating on the switch, and a variation in the strip-line width from that which produces exactly 50- Ω impedance. The gain of an MCP is, however, exponential with voltage. Therefore, even with high-trailing voltage, the signal output of an MCP would be effectively gated off.

Next, we tested the switch with pulsed x rays on the Janus laser. We used a titanium target for the x-ray source and shot 200-ps pulses of 530-nm laser light with energies of

about 10 J. We calibrated the x-ray flux by using silicon *p-i-n* diodes whose x-ray sensitivities and filtering were well known. The GaAs chip was blocked from light by a filter with about 2 μm of aluminum on Mylar to permit x-ray transmission below 1.5 keV. The result of an 8-J shot with a 2000-V bias on the switch, shown in Fig. 3, included the fast (100-ps) rise time and flatness of voltage during the bias period, which is a reasonable physical approximation of a square wave. An MCP biased by this pulse would gate on faster than the rise time because of its nonlinear increase in gain with voltage.

The calibrated *p-i-n* diode on this shot revealed that the x-ray flux from the laser-produced plasma was about 1.2 mJ/cm² at the distance of the Auston switch. Although this flux is less than the theoretical 3 mJ/cm², calculated earlier, the x-ray intensity is sufficient for good switching. The failure to switch the full half-bias voltage of 1000 V was not caused by poor x-ray sensitivity but by impedance mismatches in the

Figure 2. Auston switch response to direct, green laser light at 2500-V bias with a 530-nm trigger. The long rise time is the result of the lengthy (1-ns) laser pulse.

switch. The residual impedance mismatch and resistances produced the observed high-voltage tail, contributing to the inefficient switching. Although our prototype pulser did not switch with maximum efficiency, we could still switch 1000 V or more by simply increasing the bias voltage to about 2200 V. This example highlights how GaAs switches give us the luxury of compensating for inefficient switching by increasing the bias voltage (to about 7000 V maximum).

Conclusions

We have demonstrated that a GaAs Auston switch can isolate a voltage high enough to bias an MCP and that its sensitivity to x rays can deliver a bias pulse to an MCP. We also have shown that we can gate off the switch by using x-ray excitation with rise times of about 100 ps. The advantage of this x-ray-activated switch is that we can configure it for

Figure 3. Auston switch response to x rays at 2000-V bias. Note 100-ps rise time and flat top. Although inadequate impedance matching and residual resistance in the pulser dropped the peak voltage below the theoretical 1000-V maximum, the pulser switched more efficiently with x rays than with laser light.

an experiment and then simply leave it undisturbed to gate off pulses whenever it detects x rays.

The effective application of this prototype pulser in an experimental situation depends on the time history of the x rays of interest and the existing geometry of the spectrometers in use. If the x-ray spectra of interest exist in the early stages of a source plasma, a turn-off configuration can gate off a dc-biased MCP after the spectra have been recorded. If the

spectra of interest occur later in the plasma lifetime, a turn-on configuration can bias the MCP at a specified time after x rays are detected.

Because of the success of our laboratory experiments, we plan to use a passive GaAs-based pulser in a 25- Ω geometry with an MCP-based detector on an upcoming nuclear test.

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Streak-Camera Data Systems

Streak-Camera Systems for the Contact Event

J. J. Ronchetto, J. J. Scarafiotti, K. F. Hugenberg, and J. D. Bonlie

Because of the decreasing frequency of nuclear events, we are motivated to find techniques that generate more data of higher quality per test. Thus, the complexity of underground instrumentation has evolved along with state-of-the-art technology in an attempt to meet the requirements of high-density diagnostics.

Experiments on the Contact Event required the fielding of a downhole streak-camera module containing 16 cameras. The principal diagnostics objective was to provide a multi-faceted, high-fidelity, electro-optic streak-camera module capable of recording 90% of all Contact Event data. By spatially multiplexing 13 of the 16 cameras, as described in more detail later in this article, we increased the number of data views by 87%, with each 30-ns view consisting of more than 120 data channels synchronously timed to within a fraction of a nanosecond of each other. We used more than 4000 streak-camera data channels on the Contact Event, which is greater by a factor of 3 than the number previously used. This effort represents the largest concentration and most successful application of downhole streak-camera systems ever fielded. Because of its size and sophistication, many hardware innovations and new procedures were necessary to characterize, calibrate, and field the module.

Downhole Module

The downhole portion of the streak-camera systems was contained in a 5.5- × 5.5- × 8-ft electromagnetic interference- (EMI-) proof module, as shown in Fig. 1. The module was

located at the top of the downhole canister, approximately 70 ft from the device. The module was powered by two, separate 480-V downhole cables, either of which was capable of powering the entire module. A separate control cable handled any necessary downhole power switching. Power entered the module through a power isolation box, isolation/stepdown transformers, and then radio-frequency (rf) filters to preserve the EMI integrity of the

module. Downhole signal and trigger cables passed through a signal isolation box for the same purpose.

Two independent power legs were located inside the module. Each leg had 115-V ac and 16 A of 28-V dc available. The streak-camera systems were equally divided between these two legs for added reliability. Approximately 5.5 kW of power was dissipated in the module with all of the systems energized. Two independent, externally

Figure 1. Photograph of the 5.5- × 5.5- × 8-ft EMI-proof module containing streak-camera systems for the Contact Event.

powered signal-monitoring systems were contained within the module for measuring ac and dc voltages, selected high voltages, temperatures, pressures, and streak-camera

states. The monitors sent these signals uphole for support-system appraisal and performance analysis.

We installed a downhole, redundant, high-pressure gas-supply

system in the canister, which fed a gas-flow regulator within the module. This regulator continuously passed a mixture of 90% nitrogen and 10% sulfur hexafluoride throughout the module for protection against high-voltage breakdown. We sized the gas-supply containers and set the flow rate to permit gas flow downhole for >70 d. This same gas mixture, but from external bottles, flowed through the streak cameras and module during all aboveground testing and calibrations.

All streak-camera systems were capable of being tested downhole via a dry-run system. This approach allowed the devices and pulsed light sources to be triggered from uphole generators. The intensity and temporal position of light pulses on the streak-camera readout verified the proper operation of both downhole and uphole portions of the systems.

Streak-Camera Systems

We developed and fielded the foundation of our streak-camera systems on past events, as described in the 1988 NTES *Annual Report*.^{1,2} Figure 2 shows a typical streak-camera system and module support systems. The Contact Event incorporated three types of streak cameras and three types of streak tubes to evaluate new designs. The inventory included 11 cameras of a new design with ITT tubes, two Kentech cameras with a proprietary tube design, and three streak cameras of an older design (two with RCA tubes and one with an ITT tube).

The main feature of the new camera design is that the high-voltage power supplies are contained in a separate enclosure. Only the streak tube and its sweep and gating circuitry are in the streak-camera enclosure. This design allows many cameras to be located on a single module shelf. Using the bottom shelves for the

Figure 2. Typical streak-camera and module-support systems. The individual components of these systems are described in detail in the text.

cameras allows the fiber arrays between the nuclear detector and streak-tube photocathode to be short.

On the basis of past experience, the Kentech cameras appear to have less susceptibility to EMI than the other cameras. In addition, they have the advantage of an image intensifier located within the streak tube itself, thereby eliminating the need for an external microchannel-plate image intensifier (MCPII). The Kentech cameras are also much more compact than our other streak cameras.

Spatial multiplexing (duplexing)¹ on 13 of the cameras effectively doubled the number of data channels on these cameras. The 13 multiplexed cameras plus the three nonmultiplexed cameras gave us a total of 29 views of data with 30 ns of sweep duration per view.

Fiber arrays that carried optical signals from the various experiments to the streak-camera photocathodes entered the module through cutoff waveguides located in the module bottom, thereby preserving the EMI integrity of our module. The optical-fiber arrays for every camera view contained additional fibers for the input of calibration and test signals. We used these fibers to carry light from downhole laser-diode comb and marker generators. Comb generators produce strings of light pulses at a predetermined rate. The Contact module contained 12 such generators, which were fanned out to 58 separate fibers. A minimum of two fibers went to every streak-camera view. All of the combs ran at 500 MHz, resulting in light pulses every 2 ns along the temporal direction of every streak-camera view. These pulses provided information on sweep rates and linearity, system integrity, and system intensity changes. Two laser-diode light markers fanned out to 32 fibers that were

used for timing. We also implemented a new, fast-rising, flat-topped light marker generator. The leading edge of this light pulse determines absolute timing, and the flat-top portion is used to evaluate changes in sweep rates. The instantaneous intensity of this flat pulse at the streak-camera readout is dependent on the derivative of the sweep rate.

Every camera view also contained a light marker that was generated by x rays from the device striking a phosphor. The scintillating material used for this marker was the same as the one used on most of the nuclear detectors that provided the light input signals to the streak cameras. This nuclear-driven marker provided a timing signal that was directly related to the output of the device.

The streak cameras were read out with a two-dimensional solid-state imager using a 380- × 122-pixel charge-coupled device (CCD) array. The digitized serial data stream was sent uphole via optical fiber driven by a laser-diode transmitter.

For the first time, we shipped the module from the Atlas Facility to the Nevada Test Site (NTS) with most of the delicate electro-optic components installed. In the past, we removed components from the module at Atlas, shipped them separately in foam-filled containers, and reinstalled them on arrival at the NTS. Such disassembly and assembly was not only time-consuming but also occurred at a most inopportune moment because the systems had already been completely assembled and calibrated. We evaluated the robustness of the components and the severity of transportation loading before shipment. We tested the sturdiness of components by shaking a representative streak-camera system on a shaker table. The shipping environment was

assessed by instrumenting a simulated module load with accelerometers and recording the data during a journey from Atlas to ground zero. We then analyzed these data to ascertain the drive requirements of the shaker table necessary to determine resonant frequencies and amplitudes within the module. A value of 2.6 g represented a satisfactory acceleration loading and caused no adverse effects to our components.

Prefielding Preparations of Electro-Optic Components

Calibrations and characterizations of the components of the streak-camera module were tedious but extremely important. Components were individually characterized in laboratories at Livermore and the EG&G facility (Pleasanton, California).³ The process started with adjustment and testing of each component for its reasonable operation under various environmental testing conditions. The characterization and calibration of these components were involved and iterative processes. In addition, the cameras were temperature cycled to simulate likely variations in the field and downhole, while vital signs were constantly monitored.

We taped photographically etched resolution masks with precisely measured patterns to the streak-camera optical-fiber input faceplates and used these masks to simulate the numerous data channels from a linear optical-fiber array. Various optical signals were applied through these masks to the cameras to document their performance under differing, often adverse, conditions. The main areas of test were:

- Temporal and spatial resolutions.
- Overall gain values at various microchannel-plate settings.
- Overall dynamic range.
- Aberration analysis.

The tests showed how all of these items are interrelated.

In one common calibration source, we employed a xenon flash lamp directed into a highly reflective spherical or hemispherical surface. The resulting output has a profile with a fairly uniform light

distribution (both temporally and spatially) during the streak-camera sweep period and was used for radiant gain and flat-field measurements. Optical bandpass filters that simulated the spectra of light expected from the detectors of the individual Contact experiments were placed

between the flash-lamp source and the streak camera under test. The light pulse was concurrent with the gating of the streak camera for unswept radiant-gain measurements and synchronized with both the gate and sweep circuits for swept-gain measurements.

We performed the unswept radiant-gain measurements first because this is the easiest and most accurate of the intensity calibrations. Because some camera systems in the field are checked for their dc throughput, the dc gain of a streak-camera system must be known. A calibrated photodetector that is traceable to the National Institute of Standards and Technology is first used to measure the energy supplied by the flash-lamp source. This source is applied to the input of a streak camera, and the photodetector is used to measure energy at the output of a camera. These data are then corrected for spectral sensitivity and emission variations.

We used calibrated laser-diode comb generators to characterize the streak-camera deflection rate and linearity. Because of the triggering constraints previously mentioned, circuit adjustments were necessary to minimize turn-on delay while maximizing linearity. We used a laser-diode marker signal ≤ 1 -ns full-width-at-half-maximum (FWHM) amplitude to determine the pretrigger time required for the deflection circuits.

Figure 3 shows two, common dye-laser calibration systems we used for space-time mapping. By using a variety of dyes, we can turn the output optical wavelength over the entire visible region and beyond, from approximately 400 to 1000 nm. We performed streak-camera calibrations for the Contact Event with 600-, 520-, or 390-nm light.

The laser system in Fig. 3a is a flash-lamp-pumped, mode-locked dye laser that produces a >2 - μ s train

Figure 3. Two dye-laser calibration systems used for space-time mapping. (a) A flash-lamp-pumped, mode-locked dye laser produces a >2 - μ s train of 15-ps FWHM light impulses. Light passes through a series of thin-film pellicles that split each optical pulse into five pulses that decay in intensity and are separated in time. (b) Dye laser pumped with a LN1000 nitrogen laser. Light pulses are sent to seven optical fibers of varying lengths such that the time of flight ranged from 10 to 37 ns. The expanded source then illuminates a noncoherent fiber-array bundle fanned out and coupled through an aperture mask to the streak camera under test. This system produces a space-time-mapped image without the time-varying intensities of the pellicle system in (a).

of 15-ps FWHM light impulses. The 4.8-ns temporal separation of these 600-nm optical pulses is determined by the laser cavity length. These laser-generated light pulses are routed through a series of thin-film membrane pellicles that split each optical pulse into five separate light pulses that decay in intensity and are separated in time. The temporal separation is determined by the physical pellicle separation and the speed of light in air. Because of polarization dependencies, the pellicles do not evenly divide the intensities of delayed light pulses; however, the data contained within a single image is quite revealing. Figure 4 shows an example of a streak-camera image gathered using this source. These data give a good indication of the dynamic response of each streak camera to a fast, time-varying light signal.

The streak-camera characterization source shown in Fig. 3b is a PRA LN105 dye laser pumped with a LN1000 nitrogen laser. The spectral output of this configuration was adjusted to about 520 nm with temporal pulse widths of ≤ 500 ps FWHM. The light pulses were then input to one end of a group of seven optical fibers of varying lengths. For the Contact Event, each fiber was 4.5 ns longer than the previous fiber (i.e., the time of flight through each of the seven was 10, 14.5, ..., 37 ns). The output end of these fibers was bonded, and the outgoing light was sent through a beam-expanding lens. This expanded source then illuminated a noncoherent fiber-array bundle that was fanned out and coupled through an aperture mask to the streak camera under test. This system was sufficient to produce a space-time mapped image without the time-varying intensities of the pellicle system in Fig. 3a.

Meaningful information in a streak-camera record, such as that in Fig. 4, includes temporal resolution though a broad intensity range and geometrical mapping of both time and space. Common to all streak-camera systems are aberrations that make the quantitative analysis of event data difficult. The aberrations are due to physical limitations imposed by the state-of-the-art component design and must be well characterized for data reduction. Space-time mapping provides insight into localized aberrations over a broad range of intensities, including:

- Saturation effects.
- Temporal resolution.
- Spatial resolution.

- Geometrical distortions.
- Astigmatism.

We specified the dynamic range of our streak-camera system by determining an intensity range of operation that preserved a good signal-to-noise ratio for low intensities while not suffering from space-charge effects at high intensities. The factor limiting the dynamic range of our Contact streak-camera systems to $\leq 100:1$ was the CCD cameras. System characterizations revealed that, through the range of intensity vs counts, gains were not linear but assumed an S-like shape. However, as long as this effect remains well-defined, it is possible to perform subsequent data corrections with

Figure 4. Examples of streak-camera images from the calibration system in Fig. 3a. Such data indicate the dynamic response of each streak camera to a fast, time-varying light signal.

confidence. All laboratory data from the components of the streak-camera module were archived with the field-calibration data and were used for post-event reference.

Field Calibrations

The final intensity calibrations for the downhole streak cameras were done with one of two different light sources: a flash-lamp/integrating-sphere combination, or a pulsed-laser/phosphor system. Figure 5 shows the flash-lamp/integrating-sphere source. This calibration light source consists of two coupled, diffusely reflective, integrating spheres—a 4-in. sphere housing the flash lamp, and a larger 8-in. integrating sphere with a 2-in.-square output port. A monitor diode mounted in a port on the large sphere measured the intensity of each output light pulse in $W/cm^2 \cdot sr$. By using appropriate neutral-density and bandpass optical filters, we controlled both the intensity and wavelength of the light pulse from this

system, making it a most versatile calibration light source.

The flash-lamp/integrating sphere is well suited for the flat-field calibrations of standard downhole streak cameras. The flat-field test consisted of a light pulse that uniformly illuminated a data fiber array. The output of the array is butt-coupled to the faceplate of the photocathode of the streak camera. The system is then triggered, and the ensuing streaks are a time history of the intensity of the light pulse from all the fibers. Because the pulse amplitude is essentially constant for the relatively short streak duration, the consistency of the streak intensity with respect to time reflects the system response.

The output intensity of the flash-lamp/integrating sphere is highly uniform at the exit port and is sufficiently intense to calibrate low-gain cameras with long input fiber arrays. Because bandpass filters are interchangeable, the wavelength of the light pulse can be tailored to match

the phosphor of the detector on the experiment being measured by the streak camera. A typical downhole camera calibration consisted of four to six flat-field streak records taken at different intensities. These streak calibration records have three parts:

- The actual streak data.
- One or two comb channels, which are the time standards for the streak.
- A text file of the output intensity of the flash-lamp/integrating sphere.

The final calibration data were stored on 8-in. floppy disks for use during postshot data analysis. These data, along with data taken earlier during characterization of the streak-camera system, were used by the experimenter to correct for system idiosyncrasies in data from the final event. For field evaluation, data were manually entered into a spreadsheet program, then plotted and analyzed in the forward area. This type of quick-look analysis was essential for quality control of the calibration process, providing a good set of performance data for each streak-camera system.

Because of spatial multiplexing, at least one of the streak-tube electron beams (when unswept) is located at a spatial position along the temporal axis of the output phosphor that is always viewed by the CCD camera. During the time that the streak tube is gating on and the sweep has not yet started, any light on the data array creates electrons in the beam that are integrated into this position on the output phosphor. Images containing the flat-field intensity calibrations from flash lamps suffer from severe CCD bleeding at these positions. The main problem, simply stated, is excessive charge buildup on the phosphor screen before the sweep starts. This problem is a result of waiting for the flash-lamp pulse to reach its peak before sweeping the

Figure 5. Flash-lamp/integrating-sphere light source for final intensity calibrations on downhole streak cameras. This source consists of two coupled, diffusely reflective, integrating spheres. The smaller 4-in. sphere houses the flash lamp. The larger 8-in. integrating sphere has a 2-in.-square output port. A monitor diode on the large sphere measures the intensity of each output light pulse in $W/cm^2 \cdot sr$.

streak camera. The charge buildup causes saturation in as many as 15 to 20 rows of CCD pixels. In addition, contamination or charge spillover into other rows of the CCD can become an issue. Consequently, a portion of the intensity calibration cannot be analyzed.

We solved this problem by exciting a long-decay phosphor with a temporally short (337-nm) pulse from a nitrogen laser that was initiated after the streak-camera sweep started. This procedure alleviated the problem of excessive charge buildup, thereby eliminating blooming. Figure 6 shows a schematic of the nitrogen laser system. The laser-beam pattern was formed by two cylindrical lenses. Their function was to excite an area on the phosphor that just exceeded the input face of the mixing rod. This maximized the mixing capability of the rod while maintaining efficient energy conversion from laser light to phosphorescence. After the phosphor was excited, we used a bandpass filter to narrow the spectrum to the range of interest. The function of the mixing rod was to uniformly illuminate the fiber array in space as well as angle, at least over the fiber's full numerical aperture. This new system served as a phosphor simulator, just as the filtered flash-lamp/integrating sphere, but without the problems that the flash lamp presented to the CCD portion of the streak-camera system.

An extra calibration step was necessary for streak-camera systems that recorded spectrographic data. Although standard flat-field calibrations characterized the response of the streak-camera system, including the data array, we obtained no information on alignment or performance of active detectors and spectrometer. By running the streak cameras in a gated, nonswept mode,

performing a pseudo-integration with the CCD readout, and using a dc x-ray source, we recorded the location of the various spectral lines by the streak camera. This procedure identified the location of the various known energy peaks from the spectrometer on the streak-camera record, thus spatially calibrating and aligning the system. The detector performance could be qualitatively judged by the relative amplitude of the various spectral peaks.

We obtained timing calibrations for the streak-camera system by means of a procedure called "simultaneity." The delays of every system component in the camera trigger lines, data arrays, and timing mark channels were measured, and the total delay for each leg was calculated. By launching a light pulse into the data array, simultaneously triggering the streak camera and timing mark systems, and recording the results with the camera, we could obtain a simultaneous measurement of system timing. If the timing is correct, then the measured time delays agree with calculated delays to within several hundred picoseconds, and the light pulse on the data channel along with the time mark signal appears at the predicted location on the streak record. This simultaneity procedure ensured that

the timing between camera triggers, data arrival at the streak camera, and the appearance of timing marks were, indeed, correct.

During the fielding stage of the Contact Event, much activity took place in and around the streak-camera module. Because of the work in progress and limited space, we limited access to the module area. After the data fiber arrays were installed on the streak cameras, access to the module was further limited. Streak-camera calibrations required control of both room lights and module power, which further complicated work around the module. Because of this situation and schedule requirements, we performed our calibrations during off-shift hours. We resolved many conceivable problems by dividing the module work into two shifts.

Because of their fragile nature, we took extra measures to protect the data array fibers between the time they were installed on the streak cameras and their final installation on experiments in the canister. Clear plastic panels covered the areas of the module that had exposed fibers, and a Styrofoam "fiber highway" was constructed to protect fibers that were routed from the module to the calibration bench. This highway protected all sides of the arrays

Figure 6. Schematic of the nitrogen laser system used to solve the problem of excessive charge buildup on the phosphor screen before a sweep starts.

without limiting access to the module or calibration area. Because of these protective measures and the skills of the fiber technicians, not a single data fiber was damaged.

Summary

The streak-camera module for the Contact Event was the largest and most sophisticated downhole streak-camera platform ever successfully fielded. During this effort, we set new standards for both the quantity

and quality of vital physics data that were acquired. We are continuing to develop innovative equipment and new techniques to calibrate and support the use of these complex systems in a harsh field environment.

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Triplexed Streak Cameras

J. J. Ronchetto and J. D. Bonlie

The demand for ever-increasing numbers of high-bandwidth data channels has motivated our development of multichannel, optical streak-camera systems. The major justifications for using streak cameras are their high data-density-to-size ratio and their cost-effectiveness. On several events at the Nevada Test Site

(NTS), we have demonstrated the usefulness of spatial multiplexing (duplexing) when this technique is applied to downhole streak cameras to effectively double the number of data channels per system.¹

Although triplexing has been investigated in the past, this technique was considered to be imprac-

tical because of gating difficulties. The major success of duplexing together with a desire to improve fiscal efficiency by further increasing data density led to our reinvestigation of triplexing. In this article, we discuss some of the principles and limitations of spatial multiplexing and describe our success in triplexing the Kentech streak camera for downhole applications.

Field-Proven Configurations for Downhole Streak Cameras

The principal streak camera that we have used for both nonmultiplexed and duplexed operation is the EG&G L-CA-20 downhole streak camera, which contains an ITT F4157U streak tube. Figure 1 shows a typical streak-camera system. The standard method of introducing multiple data channels into streak-camera systems is to use a linear optical-fiber array at the photocathode window of the streak tube. This window consists of a fiber faceplate with the photocathode deposited on the inside

Figure 1. Typical downhole streak-camera system used for nonmultiplexed and duplexed operation.

surface. As shown in Fig. 2, the axis of the array is perpendicular to the temporal axis of the tube. The photocathode-generated electrons draw a two-dimensional (2D) image on the phosphor screen of the anode. The temporal dimension of the image shown in Fig. 2 is a time history of the data, whereas the spatial dimension reflects the individual fiber channels. The output intensity of each fiber channel is a function of the instantaneous input intensity of that channel with respect to time.

For a streak camera with an ITT F4157U streak tube, the output image area is limited to the 40-mm active diameter of the ITT F4113 microchannel-plate image intensifier (MCPII) tube that is coupled to the streak-tube output window. The image intensifier is required to maintain low space charge within the streak tube.² The reduction ratio of a coherent optical-fiber reducer and the rectangular size of the charge-coupled device (CCD) focal-plane array (FPA) image sensor ultimately determine the size and shape of the streak-camera record. The optical-fiber reducer has an image-reduction ratio of 2.5:1. Our CCD imager is 8.8 mm (122 pixels) in the temporal dimension and 11.4 mm (380 pixels) in the spatial dimension. The output image at the MCP screen must, therefore, be 22 mm temporally and 28.5 mm spatially to use the maximum area of the CCD imager. Any portion of an image that exceeds these dimensions will not be viewed. Measurements with our downhole streak-camera systems require temporal resolution of better than 1 ns. We have used a 30-ns-wide acquisition window, where $30 \text{ ns} / 122 \text{ pixels} = 246 \text{ ps/pixel}$.

In the nonmultiplexed mode, the first part of the image in the temporal direction can be positioned just off one edge of the FPA image sen-

sor, and the last part of the image can be positioned just off the other edge. Therefore, the gate signal can be triggered on somewhat earlier than the sweep circuitry because any light from the input data array resulting in light integrated on the anode phosphor will not be seen by the CCD chip, reducing the risk of distortions in the FPA camera owing to saturation. Consequently, the turn-on time of the gate signal is less critical and only needs to rise and become stable before the sweep moves the beam onto the imaging area. The gating-off timing is even less critical because the beam must only be extinguished before the sweep circuitry retraces the beam across the imager, which is greater than 5 ms in this particular camera. In addition, because the sweep is nonlinear during its startup, the nonlinear portion can often be positioned off the data-imaging area.

Principles and Limitations of Spatial Multiplexing

Spatially multiplexed streak cameras contain two or more linear fiber

arrays. For the duplexing mode, shown in Fig. 3, the arrays are coupled to the photocathode window and are spaced apart along the temporal axis of the tube. With two linear arrays in this dimension, a pair of 2D images are formed on the phosphor screen. Photoelectrons generated late in time from array 2 must be prevented from overwriting the rectangular phosphor area designated for use by array 1. The sweep of array-1 output must start in view of the FPA imager; thus, initial sweep linearity is critical because any sweep nonlinearity comes at the expense of distorted data on the imaging area.

In both multiplexed and nonmultiplexed operation of the F4157U tube, we have gated the photon-generated electrons by electronically pulse-gating the photocathode of the tube. This gating scheme results in a radiant extinction ratio of greater than 10^5 . During gating, the EG&G L-CA-20 streak camera varies the photocathode potential and holds the acceleration grid potential constant to minimize any coupling of the gating

Figure 2. Standard microchannel streak camera. The temporal direction represents a history of the data; the spatial direction reflects individual fiber channels.

signal to other tube elements. When spatially multiplexing this camera, a major limitation arises because the potential from the grid to photocathode not only controls the gating of the tube but also establishes an electron lens that determines image focus

and magnification. The drive signal at the photocathode must, therefore, gate the tube on and off rapidly and must become stable quickly after the gating-on transition. The photocathode components and connections within the tube form a complex

impedance that results in a gate signal at the photocathode that can become unstable and ring if the drive signal is too fast. The fastest this tube can be gated on to a stable level is about 20 ns, although we have found some tubes to be much slower. The gate off, which does not need to stabilize, occurs in about 10 ns.

Although we use an external MCPH with these streak tubes, it is impractical as a primary shuttering device because we want the FPA imager to integrate all of the light emitted from the streak-tube phosphor.

The starting position of each image along the temporal axis of the phosphor is determined by the magnification of the tube and the position of arrays on the photocathode. To retain the same temporal viewing window for each array in the spatially multiplexed mode as in the nonmultiplexed mode (e.g., 30 ns/view), we must adjust the deflection-plate circuitry to a lower sweep rate. Because the physical deflection length of each electron beam is shorter when multiplexed, we obtain an increase in data input channels at the expense of temporal resolution. The combined physical length of the sweeps in the multiplexed mode is less than that in the nonmultiplexed mode because of the imaging area lost as a result of the gate rise time and distortions produced during on/off transitions of the gating pulse.

In the multiplexed mode, the electron beam associated with array 1 will be in the view of the FPA imager during the gate-on transition, and the beam associated with array 2 will be in its view during the gate-off transition, as shown in Fig. 3. Therefore, the electron beams must be gated on quickly to prevent image-camera saturation as a result of excessive light from array 1 when it is not sweeping and then gated off

Figure 3. Spatially duplexed streak camera. For the duplexing mode, the fiber arrays are coupled to the photocathode window and spaced apart along the temporal axis of the tube.

Figure 4. Spatially triplexed Kentech streak camera with internal MCP.

quickly to prevent array-2 data from overwriting into the area designated for array-1 data. The gate signal must also become stable after initia-

tion to prevent defocusing and to provide temporally uniform radiant gain from the streak tube.

We can rather briefly summarize

the factors determining the temporal record length of a multiplexed image. The start of the time window is determined by the start of the sweep.

Figure 5. (a) Triplexed record from the EG&G streak camera. (b) Triplexed record from the Kentech streak camera. Differences in saturation effects at the start of each record are identified by an asterisk. Note the differences in uniformity between the images in (a) and (b). The Kentech image shows a lack of blooming.

The end of the window is determined by the end of the streak-camera gate pulse.

Triplexing: Our Latest Approach

One type of streak camera that we occasionally use downhole employs a streak tube containing an internal MCP. The camera system, shown in Fig. 4, uses a Kentech OSC12/L streak camera. This device is shuttered by application of an electronic pulse across the microchannel plate. The gating technique has little effect on the electron optics of the tube and eloquently supports the triplexing concept.

Because this tube has no gating or acceleration electrode, the only shuttering scheme providing reasonable extinction ratios is through control of the MCP. The gain and extinction ratio of the tube are proportional to the applied voltage across the MCP. When the MCP is biased off (MCP $V_{in} = \text{MCP } V_{out}$) and the remainder of the electrodes in the tube are powered, the radiant gain (in units of W/cm^2 at 520 nm) of the tube is about 1:1000. The maximum radiant gain of the tube is ≥ 1000 with a large voltage across the MCP [i.e., the possible radiant extinction ratio is $\geq 10^6$ (Ref. 3)]. A fast-changing electronic pulse is applied across the MCP to gate the tube. Ideally, the pulse transition would turn the tube both on and off instantaneously; however, physical aspects limit these transitions to the 5- to 10-ns region. Although the gate pulse is made to

be as close to ideal as possible, small-amplitude variations are acceptable because the instantaneous gain is the dominant variable and can be accurately characterized with flat-field measurements. This circumstance implies that any stream(s) of photoelectrons at the input to the MCP can be simultaneously shuttered on or off with an extinction ratio of $\sim 10^6$ in less than 10 ns.

Images starting on-screen using the Kentech streak camera, with its internal MCP, do not exhibit the localized bright spots that result in FPA camera saturation, compared with the EG&G streak camera. Figure 5 shows examples of flat-field triplexed images from our two types of downhole streak camera gathered with the same FPA camera. The optical source in these tests was a xenon flash lamp that had a 520-nm bandpass filter. This source illuminated an optical mask containing three linear arrays of square apertures that were 100 μm on each side with 100- μm spacing, separated along the temporal dimension of the photocathode, and with sufficient flux density during the sweep period of each streak camera to produce an average intensity from the FPA camera of 140 counts (8-bit analog-to-digital).

As is apparent in Fig. 5a, the EG&G streak-camera image has a bloomed area at the beginning of each acquisition area that results in localized loss of data. In contrast, the Kentech image in Fig. 5b shows an absence of blooming. In addition, Fig. 5a also reveals geometric distor-

tions in the spatial dimension caused by magnification changes and defocusing during gating transitions. The FPA saturation problems can be eliminated by not allowing light to hit the streak-camera photocathode prior to deflection. However, this type of control is not always possible, particularly during calibration, and it does not address the issues of defocusing and geometric distortion.¹

Summary

We have demonstrated that we can triplex Kentech streak cameras for downhole applications. The increase in data channels results in some compromises in temporal resolution or width of the acquisition window. Nevertheless, such sacrifices are well justified for downhole applications because of space limitations and cost-effectiveness. We are continuing to improve data quality while increasing data quantity in downhole streak-camera systems.

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Optical Coupling between Streak Cameras and Photometrics CCD Cameras

R. V. Mitchell

Nuclear Test Program experimenters commonly use streak cameras in conjunction with charge-coupled device (CCD) cameras to obtain time- and energy-resolved measurements in underground tests. The streak camera presents multi-channel data with temporal resolutions on the order of picoseconds as an optical image. The CCD camera converts the optical image to digital data for transmission and computer storage. Because of the high bandwidths involved, these recording systems are commonly placed in the diagnostic canister downhole. This location requires that our recording systems be compact, rugged, and able to transmit data before a shock wave arrives. Such requirements necessitate the use of fiber optics instead of lenses for optical coupling between the CCD and streak camera. In addition, because of the constraint on readout time, the CCD camera has modest spatial resolution and dynamic range.

On the Hornitos Event, we fielded two streak/CCD camera systems uphole. The uphole application relaxed the aforementioned constraints so we could use a more sensitive CCD camera and readdress the issue of optical coupling. The CCD cameras were series-200 systems from Photometrics, Ltd. These cameras have a dynamic range of greater than 2000:1 (12-bit data words) and use a Thompson 7883 CCD imager cooled to -20°C . The Thompson 7883 has 384×576 pixels on $23\text{-}\mu\text{m}$ centers. Because of the imager size, the coupling optics were

required to minify the image from the streak camera by a factor of 2.5:1.

We explored three methods of optical coupling:

1. Lens coupling (Fig. 1a).
2. One-piece fiber-optic coupling in which a fiber-optic reducer is mounted directly to the imager (Fig. 1b).
3. Two-piece fiber-optic coupling in which a fiber-optic window is mounted to the imager and a fiber reducer couples between this window and the streak camera (Fig. 1c).

This report presents the attributes and evaluates the results of each method and then discusses a spatial fringe pattern that appeared with method 3. Although method 3 is the same coupling scheme that we use on our downhole camera systems, we had not observed the fringe pattern previously.

Coupling Schemes

Table 1 summarizes the advantages, disadvantages, and measured optical throughput of the three options. The optical throughput measurements were performed by R. P. Reedy and C. W. Cochran of LLNL using a Lambertian light source. The lens was a 2.5:1 minification relay lens built by Tinsley Laboratories, Inc., and designed by Optical Research Associates¹ under a contract with LLNL. We have used this lens in laboratory systems for approximately 5 y.

The one-piece fiber-optic reducer was specified by S. Thomas of LLNL and built by Schott Fiber Optics, Inc., under a contract with LLNL.

Photometrics mounted one of these reducers to a camera. Figure 2 shows the output of the reducer with a rectangular grid as input. The geometric distortion was pronounced and unusual in that it was arch-shaped. We believe this shape is caused by distortion of the narrow section of the reducer by gravity during production. The measured

Figure 1. Schematic of three methods studied for optically coupling streak-camera output to a CCD imager: (a) lens coupling, (b) one-piece fiber-optic coupling, and (c) two-piece fiber-optic coupling. The microchannel-plate intensifier (MCPI) has a fiber-optic output, making the light source into the coupling optics Lambertian.

throughput of the reducer was also less than expected because of the way in which the reducer was made. As shown in Fig. 3, to form a rectangular island that is long enough for mounting in the imager, the reducer

must use the narrowest portion of the fiber boule and then be cut back. Therefore, although the input-to-output image size ratio is 2.5:1, the maximum minification ratio is somewhat larger and occurs in about the

middle of the island. Because the acceptance angle of a fiber reducer scales with the reduction ratio, a Lambertian light source couples less light through a 3:1 reducer than through a 2.5:1 reducer.

For the two-piece fiber-optic coupling, LLNL supplied to Photometrics four of our standard 2.5:1 reducers, which are commonly used downhole. Photometrics mounted these reducers to four camera systems. All four systems showed a spatial fringe pattern when illuminated by a focused light source. In addition, the extra interface caused

Table 1. Advantages, disadvantages, and measured optical throughput of the three coupling schemes.

Advantages	Disadvantages
Tinsley lens (7.28% throughput) <ul style="list-style-type: none"> • Spatial distortion is simple vignetting. • Software can easily compensate. • Used for ~5 y. • Well characterized. 	<ul style="list-style-type: none"> • Bulky lens. • Expensive (~\$8100/lens). • Care required to align and focus because of shallow depth of field.
1-piece fiber (6.15% throughput) <ul style="list-style-type: none"> • Small size. • Inexpensive (~\$800). • Easy to align and focus. 	<ul style="list-style-type: none"> • Spatial distortion. • Arch distortion tricky to remove. • Chicken-wire distortion seen with focused light source, and frequency components nearer to data than for Tinsley lens.
2-piece fiber (4.1% throughput) <ul style="list-style-type: none"> • Small size. • Inexpensive (~\$800). • Easy to align and focus. 	<ul style="list-style-type: none"> • Fringing pattern with focused light source, which modulates data by 7 to 10%. • Fairly high frequency components. • Difficult to correct for; pattern changes with time/temperature.

Figure 2. Output of the one-piece reducer, which was designed to be mounted directly to the imager, with a rectangular grid as input. The reducer causes the output of the grid to appear bowed or arch-shaped.

Figure 3. Construction of one-piece reducer. (a) A fiber-optic bundle, or boule, is heated and stretched to form a narrow neck near the center. The boule is then cut past the neck region such that the ratio of the input image size (far left side of the boule) relative to the image size at the cut is 2.5:1 for our application. (b) The flared area of the reducer just to the right of the neck is cut and ground down to form a straight rectangular section, or island, that mounts directly into the imager. (c) Completed one-piece reducer.

by the juncture of the fiber-optic window with the reducer decreased the transmittance.

Spatial Fringe Pattern

Figure 4a shows an image from one of our four cameras with the two-piece fiber arrangement under flat-field illumination with a focused light source, illustrating the fringe pattern. The honeycomb or "chicken-wire" pattern arises from the joints of the smaller bundles that make up the optical fiber. The chicken-wire pattern appears to some degree in virtually all fiber-optic bundles. The accompanying Fourier transform of the image (Fig. 4b) shows the frequency components due to the fringe pattern.

The fringe patterns and their intensity of modulation remained unchanged after removing the 570-nm bandpass filter, indicating that this effect cannot be attributed to wavelength interference. By using an identical reducer and a fiber-optic plug, we were able to reproduce the fringing effect by butting the two components together and rotating them relative to each other. Thus, it seemed possible that most of the fringing might be caused by a moiré'-like effect at the reducer/window interface.

When we compared flat-field intensity plots for a camera at two different light intensities, scaling up the lower-intensity plot and overlaying it on the higher-intensity plot, we found that the two plots were virtually identical. Further tests showed that the percentage of modulation due to fringing did not vary with intensity, with peak-to-peak variance ranging from 7 to 10% of the mean intensity value. (For example, if the mean value of the flat field was 2000 counts, the fringes would cause variance ranging from 1900 to 2100 counts.)

Because the intensity of modulation remains constant with light intensity, we can correct for fringing with a flat-field technique.² In this type of correction technique, the pattern must remain constant from the time the flat field is taken to the time the data field is taken. Because the technique requires division of images, even a slight change of pattern could greatly corrupt the data. Therefore, a series of temperature tests was performed to test the stability of the patterns. In these tests, we obtained a set of five flat

fields at room temperature (68°F). Then we heated the area around the fiber-optic interface to 113°F. We allowed the system to stabilize for 30 min before taking another set of five flat fields. The procedure was repeated until we obtained three sets of five at 68°F and two sets of five at 113°F. From each set of five, we computed a standard-deviation image plane, called TEMPSTABLE. We also computed a standard-deviation image plane, called TEMPVAR, using one member from each set.

Figure 4. (a) Flat-field image using a focused light source and the two-piece fiber-coupling method. Both the fringes and chicken-wire patterns are visible. (b) Fourier transform of the image in (a). The dc components are in the lower left corner. The fringing frequency components are clustered near the center of the y axis. The chicken-wire components appear as a series of dots from the origin to the bright cluster located at about 2 o'clock.

Figure 5.

(a) Fourier transform of a flat-field image using a focused light source. Both the fringing and chicken-wire components are present. (b) Fourier transform of a standard-deviation image calculated from five flat fields taken at the same temperature, called TEMPSTABLE. The lack of frequency components shows that the fringing and chicken-wire patterns were stable. (c) Fourier transform of a standard-deviation image calculated from five flat fields taken at cycled temperatures, called TEMPVAR. The components resulting from chicken wire are clearly visible, and frequency components resulting from fringing have also returned. Apparently the spatial positions of the chicken wire and fringing change somewhat with temperature, although their frequency components do not.

Figure 5 shows the computed Fourier transforms of a single flat-field image, standard-deviation image TEMPSTABLE, and standard-deviation image TEMPVAR. While TEMPSTABLE shows none of the frequency components that we see in the flat field, TEMPVAR does. This result indicates that the exact spatial positions of patterns change with temperature, but the frequency components do not. If the position of the patterns changes with moderate temperature cycling, then we can expect them to change with time, and flat-field correction would be invalid.

When a Teflon diffuser was butted up to the input of the fiber reducer to simulate a Lambertian light source, similar to what the fiber faceplate on the output of the streak camera puts out, the fringe pattern disappeared. Figure 6 shows a flat-field image and its Fourier transform. Here, the frequency components associated with the fringing and chicken wire are gone.

The setups shown in Fig. 7a and b were used to determine how the contrast transfer function (CTF) changed, depending on whether the light source was focused or Lambertian. The results shown in Fig. 7c indicate that spatial resolution is reduced for a Lambertian light source. This result was expected because a Lambertian source has a greater percentage of light entering the reducer at nonzero angles relative to the reducer axis. The Lambertian light is not as well confined by the fibers, so the spatial resolution is reduced because edges are diffused more than for a focused source. Therefore, the spatial fringe pattern may be getting swamped out in a Lambertian

source. With a microchannel-plate intensifier (MCPI) butted up to the reducer input and used as a source, we again observed no fringes. This finding probably explains why we have not seen the fringe pattern before when calibrating streak/CCD systems for downhole use.

Conclusions

The Tinsley lens is currently our coupling method of choice for uphole systems because it has been in use with Photometrics cameras for several years and is fairly well understood. As we move to larger imagers and the minification ratio

decreases, the Tinsley lens may become less appropriate. Thus, we are continuing to explore the technique of directly mounting a reducer to an imager.

Photometrics has relaxed their requirement on the length of the

Figure 6. (a) Flat-field image using a Teflon diffuser to simulate a Lambertian light source. The fringes are absent. (b) Fourier transform of (a). Frequency components associated with fringing or chicken wire are absent. The vertical line is due to distortion of the first few rows of the image because of the readout process. On-axis frequency components are due to the rectangular geometry of the imager and circular geometry of the light source.

Figure 7. Setups used to measure the contrast transfer function for a Lambertian and focused light source. (a) For the Lambertian source, a film target was sandwiched between the input of the reducer and the Teflon diffuser. The diffuser was then illuminated with an unfocused optoliner. (b) For the focused light source, an optoliner was used to focus a PR-10 television bar target onto the input of the reducer. (c) Measured contrast transfer functions for the Lambertian and focused light source show that the spatial resolution for the focused light source is noticeably better than that for the Lambertian source.

island they need for mounting a fiber-optic reducer to an imager. This change would reduce the maximum minification that the reducer would need to obtain the correct island length, thereby increasing the throughput of the reducer. One possible method for correcting the arch-shaped geometric distortion we have observed would be to pull the fiber boules vertically. The shorter island should also help reduce this problem. We are still working toward this approach to coupling because of the reduced size, cost,

complexity, and optical loss that we anticipate.

The spatial fringing pattern we observed with the two-piece arrangement scaled linearly with light intensity and showed some spatial shifting with temperature and, we may assume, with time; however, the frequency components remained unchanged. Spatial filtering should help alleviate this problem. The fringe pattern was only observed with a focused light source and was not wavelength-dependent. Because this fringe pattern was not observed with the one-piece fiber arrangement,

I believe a moire'-like pattern is generated by the interface between the fiber-optic window and fiber reducer. When the light source was such that fiber-to-fiber crosstalk occurred, the fringe pattern was swamped out.

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New Directions in Experimental Physics

Transmission Crystal Spectrometer for Measuring Hard X Rays Underground

P. O. Egan and J. K. Wobser

The spectroscopy of x rays associated with an underground nuclear detonation is a powerful diagnostic tool for understanding the detailed physics of nuclear weapons design. Experimental advances in crystal spectrometer techniques and in electro-optic data systems have greatly improved the time and energy resolution of our x-ray spectral measurements for the soft x-ray region (below 20 keV).^{1,2} In FY 1989, we designed a Transmission Crystal Spectrometer (TRACS) (Fig. 1), thereby extending the technology developed for soft x-ray experimental measurements to the hard x-ray region (above 20 keV). The new diffraction spectrometer has potentially 1000 channels of energy resolution, in contrast to the 10 channels available using our previous diagnostic tool (SPECTEX), for measuring hard x rays. We can, therefore, now view the fine details of the hard x-ray signal of a nuclear device.

Crystal Spectrometer Development

In the past, the standard measurement technique for making hard x-ray measurements was the use of absorption-edge filters and fluoroscopes to define bandpass regions of the spectrum. We observed approximately 10 spectral energy channels using SPECTEX—a standard filter-fluorescer assembly. The channels were determined by the choice of fluorescence thresholds and absorption edges. Although SPECTEX

proved to be a powerful diagnostic tool, the 10 spectral channels limited our view of the fine details of the energy spectrum. Also, a spectrum with a complicated shape was extremely difficult to analyze because of SPECTEX's reliance on absorption edges. Therefore, we wanted to find a new method for measuring hard x rays.

Although we successfully applied the crystal diffraction method for reflection geometry in downhole measurements of soft x rays, this method had technical problems at hard x-ray energies. The Bragg reflection angles become quite small at high energy, and the reflection angles approach grazing incidence.

The Bragg reflection law, which determines the energy dispersion in x-ray crystal diffraction, is given by $n\lambda = 2d \sin\theta$, where λ is the x-ray wavelength that is related to its energy by $\lambda \text{ (nm)} = 1.2396/E \text{ (keV)}$, d is the crystal interplanar spacing, n is the diffraction order, and θ is the angle of incidence for diffraction. Bragg's law shows that even for the smallest practical crystal $2d$ spacing of 0.16 nm, the diffraction angle at 100 keV is just over 4 deg. Such small angles from crystal planes parallel to the crystal surface make reflection spectroscopy difficult.

The problem was solved using a technique known as transmission crystal spectroscopy. Rather than

Figure 1. TRACS undergoing x-ray calibration. X rays from the calibration source (rear of photo) simulate the actual event spectra. Two of the crystals can be seen inside the box-like vacuum enclosure of the TRACS. The fiber-optic imagescope is the black, hose-like object draped around the spectrometer body.

choosing diffraction planes parallel to the surface of the crystal (reflection geometry), we chose planes perpendicular to its surface (transmission geometry) as shown in Fig. 2a and b. X rays that satisfy the Bragg law are still Bragg-reflected while being transmitted through the crystal. That is, the x rays still have small Bragg angles, but they strike the crystal surface at near normal incidence angles, making it technically easier to build a practical spectrometer. The transmission technique is applicable when the x rays are so energetic

they will not be appreciably absorbed in the crystal. We made the 5- × 7-cm crystals thin enough (0.5 mm) so absorption is not a problem, yet thick enough so diffracted intensities are comparable to the reflection spectroscopy method.

The Bragg diffraction disperses the x-ray energies spatially; less energetic x rays are deflected to larger Bragg angles. The problem of measuring the x-ray spectrum then becomes one of spatially imaging x rays downhole. TRACS can do this well, both in terms of position resolution and timing.

TRACS Design

In addition to crystal diffraction, TRACS is also similar in design to the earlier NTES soft x-ray spectrometers (e.g., VJACS, HYJACS) in that it uses cylindrical focusing. However, the focusing method is not the Johann geometry of these earlier instruments, but rather the Cauchois geometry³ shown schematically in Fig. 2c. When the transmission crystal is elastically bent to a cylindrical figure (by clamping it between precisely machined surfaces), monoenergetic x rays from a diffuse source on the convex side of the crystal focus to a line along the Rowland circle. The radius of the Rowland circle is half that of the bent crystal. A detector mounted on the Rowland circle views the spectrum of diffracted x rays that are dispersed in one dimension by the Bragg relation. An example of the energy-resolving capabilities of such an instrument can be seen in Fig. 3, which shows the spectrum obtained by one of our crystals viewing a source of tin fluorescence x rays.

In our downhole TRACS, we field three separate crystal/detector combinations to cover the energy range from 20 to 110 keV. Although, in principle, a single crystal could cover the region, we prefer to use multiple spectrometers and different crystal $2d$ spacings for various reasons: (1) to give a choice of resolution, (2) to provide overlapping coverage, and (3) to provide insight to systematic effects in the measurement (e.g., contributions from higher-order reflections). We chose three different crystals: α -quartz, silicon, and lithium fluoride. The crystals were cut with quartz (310), silicon (111), and lithium fluoride (200) diffraction planes perpendicular to the surface.

Figure 2. (a) X rays that satisfy the Bragg equation are reflected from crystal planes. For reflection geometry, the planes are parallel to the surface, and at hard x-ray energies, the Bragg angle, θ_B , is quite shallow, making spectrometer design complicated. (b) In transmission geometry, the planes are perpendicular to the crystal face, and the x rays enter and leave the crystal at almost normal incidence. (c) In the Cauchois focusing spectrometer, x rays from a diffuse source are diffracted from a cylindrically bent transmission crystal and focus to a point (a line in three dimensions) on the Rowland circle, whose radius is half that of the bent crystal. Less energetic x rays (the dashed lines in the figure) are diffracted through a larger Bragg angle and focus at a different spot on the detector.

Figure 4 shows a schematic diagram of TRACS and the electro-optic recording system. The three x-ray spectra diffracted from the 0.5-mm-thick crystals pass through slits that reduce background contributions. The x rays continue on and pass through a set of filters that provide energy calibrations with absorption-edge fiducials. Then the x rays strike a thin WL1198 phosphor (cadmium sulfide doped with indium) that is deposited on a fiber-optic faceplate mounted on the Rowland circle. The phosphor converts x rays to visible light and is the first stage of our detector. Some fraction of the x rays eject a photoelectron in the phosphor, which in turn excites the phosphor. The phosphor emits yellow-green visible light at 520 nm. The emitted light of the WL1198 phosphor has a particularly fast time decay—less than 200 ps. Thus, the spectrometer converts an x-ray beam to a spectrally dispersed visible output, which can be imaged using downhole techniques and then read out aboveground.

Figure 3. A typical x-ray spectrum from TRACS. The diffracting crystal is 0.5-mm-thick quartz (310) bent to a 30-cm radius. The incident x rays are the K_{α} lines from a tin fluorescence source. The x axis shows the spatial dispersion of the two x-ray lines along the detector Rowland circle.

TRACS Electro-Optic Readout

The phosphor light from each detector is coupled to seven 5.5-m-long fiber-optic imagescopes. The imagescopes transport a spatially coherent image of the detector light to an electromagnetic pulse- and radiation-shielded module for further processing. Only five of the seven imagescopes view the actual dispersed spectrum; the other two are used for background analysis.

Once inside the module, one imagescope spectra view from each detector is split off and combined into a single fiber-optic array. The array is fed to a single downhole streak camera that is intensified with a microchannel plate. The streak camera produces a two-dimensional spatial image on a P-20 phosphor at its output: one dimension corresponds to x-ray energy and the other dimension to sweep time, whereas brightness corresponds to x-ray intensity. By selecting suitable

Figure 4. Schematic diagram of TRACS and the electro-optic recording system. The three crystals view two x-ray beam lines. Because most x-rays are transmitted through the crystals, two crystals can be piggybacked on one line of sight. The diffracted x rays produce light in the detector (WL1198 phosphor). Only one imagescope arm is shown for clarity.

streak-camera parameters, we can attain a time resolution of the x-ray signal of 0.3 ns. The visible streak-camera output is recorded by a charge-coupled device (CCD) array that is digitized downhole. Then the data are sent via fiber optics to the surface, where they are recorded in computer memory.

The other six imagescope spectra from each detector (four signal, two background) are amplified by a gated microchannel-plate intensifier and viewed by a Reticon linear photodiode array as part of an electronics package known as the Spectroscopy Array Camera System (SPACS). The diode array consists of 1024 separate optical sensors, side by side, on a 2.54-cm-long integrated circuit. The array integrates the light

falling on it from the detector and, when read out, provides 1024 spatial (hence, in our spectrometer, energy) channels. As in the CCD array for the streak camera, the SPACS digitizes the analog electronic signal downhole and sends it to an above-ground computer on fiber optics.

Conclusion

We are fielding a spectrometer that will potentially enhance the energy resolution for downhole hard x-ray measurements by two orders of magnitude—from the 10 channels of SPECTEX data to the 1024-channel TRACS. The spectrometer is broadband; a single crystal can cover the entire hard x-ray region. The experiment exploits recent developments in electro-optic technology, and it allows us to bring

the power of precision, above-ground laboratory spectroscopy to the challenging environment of underground nuclear testing.

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Fiber-Optic Gamma-Ray Spectrometer

M. J. Moran

Measurements of gamma-ray emissions have been fundamental to nuclear-test diagnostics. Such measurements often include a series of gamma-ray spectral measurements that provide more detailed information about device performance. Because the data must be recorded during a single signal pulse, gamma-ray spectral data are measured with Compton spectrometers that allow signals from different gamma-ray energies to be generated in physically separate detectors (see Fig. 1). In this approach, gamma rays are converted to energetic electrons through Compton scattering in a suitable target. Magnetic analysis of the electrons physically separates them according to their energy. The

characteristics of Compton scattering allow the initial gamma-ray spectrum to be inferred from the corresponding measured spectrum of Compton electrons.

Compton spectrometers have numerous advantages for downhole nuclear diagnostics. They are physically rugged and can survive the rigors of downhole operation reliably. Their basic design is quite simple, and they can be configured to optimize the return of data for specific experiments. However, the process of optimization almost always involves improving one characteristic at the expense of another. For example, low Compton-scattering efficiency can be partially compensated for with thicker scat-

tering targets, but electron scattering in the target may then reduce the inherent resolution available from the instrument. The energy resolution associated with a given detector size might be improved by using a smaller one, but then the detector may generate only a proportionally smaller peak signal, thus limiting the dynamic range of an experiment. Despite these difficulties, Compton spectrometers have been successfully fielded in downhole experiments to study phenomena over a wide range of gamma-ray energies.

It is now possible to complement existing gamma-ray spectroscopic capabilities by detecting Compton electrons with an optical signal

directly in the core of an optical fiber. With this approach, the optical signal is generated by the Cherenkov effect in the fiber core. This signal is then transmitted through an optical fiber to an uphole or downhole recording station. Such an approach would have major advantages in signal bandwidth and in the number of detectors that could be included to cover a given range of electron and, thus, gamma-ray energy. The bandwidth advantage derives from the instantaneously generated Cherenkov light signals that can be recorded directly on streak cameras with better time resolution than is possible with conventional electrical signal systems. The optical-fiber approach may allow the use of more detectors over a given spectral range because the $\sim 150\text{-}\mu\text{m}$ -diam fibers can be placed much closer together than the 16-mm-diam (or larger) $p\text{-}i\text{-}n$ diodes that also are used for spectral measurements. Furthermore, the optical-fiber approach can take advantage of systems developed by the Nuclear Test Program during the past decade for fielding optical fibers.

Demonstration of the FOGS System

A prototype fiber-optic gamma-ray spectrometer (FOGS) will demonstrate the generation and transmission of gamma-ray spectral data in optical fibers in an upcoming test event. Figure 2 shows a schematic of the spectrometer geometry. The experiment includes a conventional gamma-ray spectrometer (so-called GASP device), so we can compare the FOGS data with those from GASP.

As shown in Fig. 2, Compton electrons scatter from a 0.5-mm-thick beryllium converter. This converter injects about 10^{-4} Compton electrons per gamma ray into the magnetic analyzer. The magnet deflects the

electrons and, after a 90-deg bend, gives a first-order focus at a point whose position is proportional to the electron energy. For different gamma-ray energies, focal points lie along a line at 45 deg to the initial gamma-ray direction, where a thin window allows electrons to escape from vacuum into the air. Optical fibers situated along the vacuum window intercept three different electron energies, with the fibers oriented so that their axes are at 45 deg to the electron velocities. The 45-deg angle of incidence optimizes injection of Cherenkov light into the fiber for transmission to a remote recording station. One advantage of this arrangement is that the optical fibers are exposed only to the electrons they are intended to measure. This setup reduces or eliminates difficulties associated with radiation-induced darkening of the fibers during the experiment.

Figure 1. Basic Compton spectrometer geometry. Incident gamma rays scatter energetic (Compton) electrons into a magnetic-field region that spatially separates them according to their energy and delivers them to corresponding detectors.

The different parameters of the spectrometer combine to give roughly 12% energy resolution at any given point. Since Cherenkov light intensity is proportional to electron flux (which itself is proportional to the gamma-ray intensity), a recording of the Cherenkov light intensity can be interpreted in terms of the corresponding gamma-ray intensity history.

Figure 2. FOGS geometry. This schematic shows how the Compton spectrometer geometry can be adopted to generate a Cherenkov light signal in the core of an optical fiber.

Components of the FOGS system represent familiar, tried-and-true technology. Compton scattering in the beryllium converter is accurately described by the Klein-Nishina formula. Elastic scattering of the Compton electrons in the beryllium converter (before they escape) alters the Compton electron distribution in ways that are well described by Moliere's theory and Monte Carlo computer modeling. We have incorporated these issues into the FOGS design. The behavior of the magnetic spectrometer is well understood, and details of its performance have been calibrated in experiments at the EG&G Santa Barbara Office (SBO) linear accelerator.

Electron detection by the Cherenkov effect in optical fibers has become familiar through a history of fiber-optic alpha-measurement (FOAM) experiments that use precisely this technique. Furthermore, a series of experiments at the SBO linear accelerator verified the absolute efficiency of Cherenkov light

injection into the core of optical fibers by relativistic electrons. The results of these measurements indicated that the injection efficiency was within about 15% of what would be predicted by a simple theoretical description. Experiments, such as this one, that measure absolute efficiency are extremely difficult to perform; thus, the 15% discrepancy could arise entirely from the net effect of numerous experimental uncertainties.

Figure 3 shows the geometry for injection of Cherenkov light into an optical fiber. When an electron travels through an optical medium with speed v , Cherenkov light is radiated into a hollow cone with half-angle θ_c given by:

$$\theta_c = \cos^{-1}(1/n\beta), \quad (1)$$

where n is the refractive index of the medium, and $\beta = v/c$, where c is the speed of light in vacuum (see Fig. 3a). Equation (1) may not be exact for the interior of a microscopic

fiber, but it is a good approximation because the 50- or 100- μm fiber diameter is still much greater than an optical wavelength. However, an optical fiber transmits light only if it is within a critical angle ξ of the fiber axis. Note that the numerical aperture of a fiber is $\sin\xi$, with ξ having typical values of about 15 deg. For normal optical materials in the visible spectral region, $n \approx 1.5$. Therefore, $\theta_c \approx 45$ deg for common optical materials when $\beta \approx 1$ (always satisfied in the present case). Thus, only a portion of the Cherenkov cone can be within the "acceptance aperture" of the optical fiber, and that portion will depend on the relative orientation of the electron velocity and the fiber axis. The geometry in Fig. 3b can be used to demonstrate that this portion F is given by:

$$F = \frac{1}{\pi} \cos^{-1} \left(\frac{\cos\xi - \cos\theta_f \cos\theta_c}{\sin\theta_f \sin\theta_c} \right), \quad (2)$$

where θ_f is the angle between the fiber axis and the electron velocity. For the FOGS spectrometer, F is about 0.11.

The production of Cherenkov light as an electron travels through an optical material is described by:

$$N_c = 2\pi\alpha \left(\frac{l}{\lambda} \right) \left(\frac{\Delta\lambda}{\lambda} \right) \sin^2\theta_c, \quad (3)$$

where N_c is the number of photons having wavelength λ within bandwidth $\Delta\lambda/\lambda$ generated as the electron travels over path length l , and α is the fine-structure constant, with $\alpha \approx 1/137$.

For an electron crossing a 100- μm optical fiber at an angle of 45 deg and radiating 440-nm-wavelength photons into a 5% bandwidth, Eq. (3) gives an average (over the fiber thickness) of about 0.3 photons radiated per electron. Although this

Figure 3. Geometry for injection of Cherenkov light into an optical fiber. (a) Basic Cherenkov geometry. (b) As an electron passes through a fiber, a fraction $F = \delta\phi/2\pi$ of the Cherenkov cone is injected into the fiber core. The fraction F and other parameters are discussed in more detail in the text.

is not an enormous number, it is still quite good considering the short radiating pathlength available in the fiber. When combined with the fraction F from Eq. (2), the net result is that about 0.03 photons are injected into the fiber core for every electron that passes through.

The overall response of the FOGS can be estimated by including the conversion of incident gamma rays into electrons that intercept the fiber. The basic conversion efficiency given above is about 10^{-4} electrons per gamma

ray; however, a final factor must be considered as well. The optical fiber is so small that only a small portion of scattered electrons actually intercepts the fiber. In the present case, this efficiency is only about 2×10^{-3} . Thus, the overall FOGS sensitivity becomes about 6×10^{-9} photons per incident gamma ray, which is equivalent to about 2.7×10^{-27} W/gamma ray·s⁻¹. Although this sensitivity appears to be quite low, it is nevertheless sufficient to generate useful data from a nuclear explosion.

Conclusions

The current FOGS experiment is intended to serve as a prototype demonstration to test whether signals will be recorded with the predicted intensities and to verify that the results are consistent with other data from the event. If our expectations are realized, we will have successfully added another set of options in obtaining downhole gamma-ray spectral measurements.

NUMO: A New Fusion Neutron Diagnostic

M. J. Moran

Inside a nuclear explosive, hydrogen fusion can take place in a dense plasma. The fusion process can contribute significantly to the explosive yield either directly as an energy source or by producing neutrons that augment a fission source. Optimizing the fusion contribution to an explosive's overall performance is one of the goals of explosive design. Such optimization requires that we obtain accurate data on the physical processes within the plasma.

High-energy gamma rays, neutrons, and neutrinos are the penetrating radiations emitted in hydrogen fusion. A time-dependent measurement of these fluxes should yield the fusion energy-production rate. The key feature of a successful flux measurement is providing spectral, or energy, resolution. Energy resolution in the gamma-ray diagnostic isolates the relatively narrow fusion gamma line from other background gamma rays. Similarly, neutron

energy resolution isolates those neutrons associated with fusion reactions and helps to eliminate confusion in data that arises from the direct relation between a neutron's energy and its speed. Neutrons differing in time of birth in a fusion reaction can arrive at a distant detector simultaneously if they have appropriate speeds (energy). Conversely, neutrons of differing energies emitted at the same time will arrive at a detector over a relatively long time period. Thus, without energy discrimination (spectral resolution), we cannot determine the unique time signature of the source.

A new diagnostic technique, a neutron monochromator called NUMO, provides sufficient spectral resolution to study source time history with neutron flux measurements. Briefly stated, NUMO uses magnetic spectrometry of recoil protons to provide energy resolution in the neutron flux measurement. This technique uses passive components

downhole and takes advantage of recently developed high-field-strength magnetic materials. The basic NUMO technique can be extended to allow observation of selected portions of the emitting plasma, adding spatial dependence to the time-resolved measurement of fusion burn.

Theory

Downhole measurements of absolute neutron flux often rely on measuring the current of protons emitted from a hydrogenous foil located in the neutron line of sight. The absolute accuracy of this proton-recoil technique is ensured because the cross section for neutron-proton elastic scattering is well known, as are energy-loss mechanisms for protons as they travel from foil to detector. The protons are easy to stop (detect), and detection efficiencies are accurately determined. For low neutron fluxes, high-sensitivity *p-i-n* diode detectors with a gain of about

Figure 1. NUMO component arrangement. Protons are scattered from a 25.4-mm-thick foil located 2.5 m from a source. Those protons to be detected are scattered at 30 deg from the neutron beam, dispersed by a 0.8-T sector magnet, and then focused onto a passive Faraday cup detector 1.5 m from the magnet.

1 million are used. Absorbers placed in the proton path can give crude energy discrimination, essentially providing a high-pass threshold filter. Nevertheless, we require more precise energy definition to accurately measure the source time dependence.

We can demonstrate the relation between the spread of energies in a detected neutron flux and uncertainty in the time of birth at the source by the following analysis. In hot-plasma deuterium-tritium (DT) fusion, neutrons are emitted with energies in a band ΔE near 14.1 MeV. The speed v_n of a neutron of mass m_n is uniquely related to its energy E by:

$$v_n(E) = (2E/m_n)^{1/2}. \quad (1)$$

For 14.1-MeV neutrons, v_n is approximately 5.2×10^9 cm/s. The energy band ΔE is, therefore, related to a velocity band by:

$$\Delta v/v \approx 1/2(\Delta E/E). \quad (2)$$

Thus, a 5% spread in energy corresponds to a 2.5% spread in velocities. If neutrons travel a distance d to a detector, the transit time, which is energy-dependent, will be

$$t(E) = d/v(E). \quad (3)$$

From these relations, the fractional arrival-time spread associated with an energy band may be written as:

$$\Delta t/t = -1/2(\Delta E/E). \quad (4)$$

These equations can be combined to define a neutron-diagnostic "uncertainty principle" that takes the form:

$$\Delta E \Delta t \approx -(d/4)(\Delta E/E)^2 2mE. \quad (5)$$

Equation (5) notes the relation between uncertainty in source-emission time Δt , given the spread

in energies ΔE detected by a neutron diagnostic. Clearly, for precise definition of the source time dependence, the spread in detected energies must be made small. NUMO uses magnetic spectrometry of recoil protons to minimize the spectral spread detected, while still maintaining measurable flux levels within that selected energy band.

Experimental Design

Similar to the more routine neutron diagnostics described earlier, NUMO detects protons scattered from a hydrogenous foil directly exposed to the neutron flux. Proton energy (and, therefore, velocity) is uniquely related to the scattering angle and to the energy of the neutron from which it was elastically scattered. Limiting the experiment's sensitivity to a narrow range of neutron energies requires that only protons having a correspondingly narrow range of energies be detected. We accomplished such detection by collimating the proton beam to select a desired scattering angle and by using magnetic spectrometry to select the desired proton energies. A detector placed in the focal plane of this magnetic proton spectrometer will intercept protons within a narrow energy band about a selected central energy.

In practice, several subtle features of the proton portion of the diagnostic affect the overall precision of NUMO. Protons lose energy in the hydrogenous foil, thus degrading the unique relation between proton and neutron energy. This makes choice of foil thickness a compromise between selecting a foil that is as thin as possible to maintain good energy resolution, and choosing one that is

not so thin as to make proton flux too small to measure. The finite collimation diameter of the neutron and proton beams also degrades the energy resolution of the experiment through the relation between proton energy and scatter angle. Again, reduced collimation diameter improves resolution at the cost of signal amplitude. Finally, the magnetic spectrometer itself also introduces trade-offs in resolution vs intensity. All parameters must be balanced in the design of an experiment to be fielded on a nuclear test.

Figure 1 shows the design features for a NUMO with acceptable sensitivity (about 5×10^{-28} C/incident neutron) and 1-ns time resolution. In this example, protons are scattered from a 25.4- μm -thick foil located 2.5 m from the source. The protons to be detected are scattered at 30 deg from the neutron beam. They are dispersed by a 0.8-T sector magnet 2.1 m from the foil and are focused onto a passive Faraday cup detector 1.5 m from the magnet.

The temporal definition of NUMO is limited by the following terms:

- Temporal dispersion of neutrons traveling from the source to the scattering foil. Assuming that NUMO selectively detects neutrons within a 2% spread in energy about a central energy E results in an initial time-of-flight spread of $\Delta t_1 = 36.1d(E^{-1/2})\Delta E/E$, where d is in meters and E is in MeV. For the geometry shown in Fig. 1 and 14.1-MeV neutrons, $\Delta t_1 = 0.5$ ns.
- Uncertainty due to scattering into a finite range of angles.

Given the geometry of Fig. 1, the fractional proton-accepted energy spread is approximately $\Delta E_p/E_p = -2(\tan\theta_s)\Delta\theta_s = 0.012$.

- Uncertainty due to proton energy loss in the foil. Monte Carlo calculations indicate that the fractional energy spread from this effect is $\Delta E_p/E_p = 0.012$ for a 25.4- μm -thick CH_2 foil.

These terms add in quadrature to give a fractional energy spread of 0.017, which is less than, but quite close to, the 2% resolution of the magnetic monochromator. If the detector size is such that it intercepts protons within a 2% band of energies at the spectrometer output, then the spectrometer will contribute a time uncertainty of $\Delta t_2 = 0.8$ ns. Adding Δt_1 and Δt_2 in quadrature gives an overall time response of about 0.93 ns.

Conclusions

NUMO represents a valuable new technique for measuring details of fusion reaction rates that are not accessible by traditional diagnostic techniques. Variations of the system we have described could add spatial resolution, further experimentally defining features of fusion-burn processes in nuclear explosives that we could only calculate in the past.

A 100-fs Laser Facility with Potential Intensities of 10^{19} W/cm²

W. E. White

High-peak-power lasers have long been used as one of the primary tools in studies of atomic, plasma, and x-ray laser physics. However, the lasers in this type of research are often large and expensive, thus placing them out of the reach of many scientists. With the development of lasers capable of producing pulses with a temporal full width at half maximum (FWHM) of less than 100 fs, a new level has been achieved in the evolution of high-peak-power lasers and associated physics research.^{1,2} Because of the ultrashort nature of these pulses, amplification to a relatively modest energy level results in peak powers comparable to those produced by an extremely large laser, such as Nova. For example, a 100-fs pulse with an energy of 1 J has a peak power of 10 TW; focusing this pulse into a 10- μ m-diam spot yields a power density of 1.2×10^{19} W/cm². An ultrashort-pulse laser of this type adds a new dimension to many experiments by allowing the investigation of temporal response of a system with previously unattainable resolution.

One application of such a laser is the production of thin, solid-density plasmas. Hydrodynamics experiments can then be performed in the previously unattainable regime of solid-density materials at high temperatures. Production of plasmas in extreme states also allows us to investigate the kinetics of ionization imbalance and the associated photopumped or recombination x-ray laser schemes. This suggests the possibility of femtosecond-duration x-ray pulses, which, in and of itself, opens a new realm of physics.

High-power, ultrashort pulses also provide a means of investigating strong-field physical phenomena, such as the nonlinear optical response of materials with field strengths that were previously unattainable.

In pursuit of such research goals, we are building a laser system to provide 1 J of energy in a pulse with a FWHM of 100 fs or less. Our system is designed to meet these specifications with a high-quality spatial profile, allowing focusing to near the diffraction limit and power densities on the order of 10^{19} W/cm². Our laser will be a key component of a research laser facility that will make 100-fs, 10-TW pulses available to researchers investigating phenomena ranging from basic atomic and plasma physics to high-bandwidth measuring devices and beyond. Furthermore, our laser is designed to balance state-of-the-art output characteristics with the stability and reliability essential for a user facility.

Short-Pulse Production

Several key technological issues must be addressed if an ultrashort-pulse laser system is to be successful. Field strengths in pulses of the power range of interest are so large that all materials, including system components, exhibit a nonlinear response. To eliminate these effects in the later stages of amplification, we are using a technique known as chirped-pulse amplification (CPA), in which the pulses are temporally stretched to a much lower power level, amplified, and then recompressed to the original temporal width. Furthermore, optical pulses

with a temporal width of about 100 fs are Fourier-transform-limited to a very large bandwidth (by laser standards). This technique eliminates many of the more common lasing materials and, in fact, implies that our system will probably require more than one type of gain medium. The use of multiple gain media immediately suggests that we may encounter problems because of lasing-frequency mismatch between different lasing materials, suggesting, in turn, that some type of frequency shifting or downconverting techniques may be required. Finally, diagnostic requirements of femtosecond laser pulses are obviously well beyond the current state of the art in electronics, thus requiring autocorrelation or cross-correlation techniques for temporal measurements on these short time scales.

Production of pulses with a temporal width of no more than 100 fs requires a gain medium capable of providing at least 147 cm^{-1} of bandwidth (5.8 nm for 630-nm pulses). This requirement implies that either an organic dye or the relatively new material Ti:Al₂O₃ (Ti:sapphire) must be used as the gain medium. An energy requirement of 1 J/pulse practically eliminates dye as a suitable choice, at least for the final output stages of the system. However, a Ti:sapphire laser oscillator capable of directly producing 100-fs pulses has yet to be demonstrated. Therefore, our system is based on a hybrid design consisting of a mode-locked dye laser producing the ultrashort pulses and Ti:sapphire capable of amplifying these pulses to 1-J energy levels.

At present, there are two well-understood techniques for producing sub-100-fs pulses directly from a laser. The first is commonly referred to as a synchronously pumped dye laser and was the first laser to directly produce pulses shorter than 100 fs (Ref. 1). This type of laser can produce pulses as short as 70 fs with an energy of ≈ 5 nJ/pulse. A major advantage of the synchronously pumped laser is that it operates with a broad range of dyes at a variety of wavelengths, including the 780- to 800-nm range that is required if Ti:sapphire is to be used as an amplifying medium. Other advantages include the ability to be externally clocked and commercial availability.

A colliding pulse mode-locked (CPM) laser is the second means of generating pulses shorter than 100 fs (Refs. 2 and 3). The cavity configuration shown in Fig. 1 produces the shortest pulses available (27 fs) directly from a laser⁴ with a pulse energy of <0.4 nJ. Although the CPM laser will operate in the 780- to 800-nm wavelength range,⁵ it cannot be externally clocked and is commercially available in kit-form only. Also, the CPM and synchronously pumped lasers produce pulses at 775 nm, but neither provide the degree of stability and reliability at this wavelength we would require from a laser facility in which the emphasis is on the experiments being performed rather than on the laser itself.

The CPM laser, when operated in the more common 610- to 630-nm-wavelength range, exhibits a significantly higher degree of stability and reliability than other sub-100-fs lasers. Therefore, in addition to a technique for downconverting to the

780- to 800-nm-wavelength range, we selected the CPM laser for our system. As shown in Fig. 1, the CPM laser is a modified ring dye laser in which the gain jet (Rhodamine 6G in ethylene glycol) is pumped by 3.5 to 4.5 W of 514-nm continuous-wave (cw) light from an argon-ion laser. Colliding pulse mode locking is a passive mode-locking scheme, where counterpropagating pulses must collide within the saturable absorber jet (DODC iodide in ethylene glycol) for the net cavity losses to be low enough to allow lasing. The intercavity four-prism sequence provides a means of tuning the group velocity dispersion (GVD) of the cavity to a value that

produces the desired temporal pulse width.⁶ Table 1 lists the typical operating characteristics of the CPM laser used in this laser system.

Frequency Downconversion

The CPM laser we selected for our system produces extremely stable sub-100-fs pulses in the range of 610 to 630 nm. These pulses must then be frequency downconverted to the 780- to 800-nm-wavelength range for amplification in Ti:sapphire. This conversion is accomplished by a technique known as continuum generation, which is a nonlinear process based on the optical Kerr effect. The optical Kerr effect results when strong electric

Table 1. Typical operating characteristics at various stages throughout the laser system.

Parameter	CPM stage	Intermediate stage	Final stage
Wavelength	630 nm	630 nm	780–800 nm
Repetition rate	90 MHz	10 Hz	5 Hz
Energy	2 nJ	1 mJ	1 J
Pulse width	30–400 fs	100 fs	100 fs
Peak power	6 kW	1 TW	10 TW
Focusability (diam)	6 μ m	6 μ m	8 μ m
Power density	10^6 W/cm ²	10^{17} W/cm ²	10^{19} W/cm ²

Figure 1. The colliding pulse mode-locked laser, which is capable of generating pulses shorter than 100 fs. The cavity configuration shown here produces the shortest pulses available (27 fs) directly from a laser with a pulse energy of <0.4 nJ.

fields are applied to a dielectric material, in this case ethylene glycol. If the electric field applied to a dielectric material is strong enough, the polarization can be written as a power series expansion in the applied field E , as follows:

$$p = \chi_1 \epsilon_0 E + \chi_2 E^2 + \chi_3 E^3 + \dots, \quad (1)$$

where χ_1 represents the linear susceptibility, and χ_2 and χ_3 represent the higher-order nonlinearities in the response of the dielectric. The second term, χ_2 , is zero for all materials except piezoelectric crystals. Therefore, if we ignore the second term and all orders higher than 3, the electric displacement is

$$d = E[\epsilon_0(1 + \chi_1) + \chi_3 E^2]. \quad (2)$$

Thus, the dielectric constant ϵ is

$$\epsilon = \epsilon_1 + \epsilon_2 E^2, \quad (3)$$

where $\epsilon_1 = \epsilon_0(1 + \chi_1)$, and $\epsilon_2 = \chi_3$. Since the index of refraction can be expressed as $n = (\epsilon/\epsilon_0)^{1/2}$, we now have

$$n = n_0 + n_2 E^2, \quad (4)$$

where $n_0 = (\epsilon_1/\epsilon_0)^{1/2}$, and $n_2 E^2$ represents the nonlinear variation in the index of refraction. Consequently, the index of refraction is nonlinearly dependent on optical intensity. The nonlinear dependence of the index of refraction on applied electric field implies that, as the pulse passes through the ethylene glycol, the index of refraction will pick up a time dependence. Because light passing through an object of length L and index of refraction n experiences a phase shift $\Delta\phi = nL/\lambda$, the transmission of the pulse through

ethylene glycol will induce a time-dependent phase shift in the pulse itself. This is usually referred to as self phase modulation (SPM) and results in frequency "chirp" (time-dependent frequency sweep) and increased bandwidth of the pulse. In the regime of extremely strong fields, the phase shifts can be severe enough to produce a pulse of white-light continuum that extends from the violet to well beyond the infrared end of the visible spectrum.^{7,8}

CPM Amplification

Prior to generation of the continuum pulses, the CPM pulses must be amplified from <0.4 nJ/pulse to >1 μ J/pulse. Amplification is initially carried out in a six-pass "bow-tie" amplifier based on the design of Knox and coworkers.^{9,10} The gain cell (sulforhodamine 640) of this amplifier is pumped at a repetition rate of 10 Hz by 532-nm pulses from a Quanta-Ray GCR-4 Nd:YAG laser. A Malachite Green saturable absorber is inserted between the fourth and fifth pass to minimize amplified spontaneous emission (ASE).

Although output pulses from the bow-tie amplifier are capable of producing a usable white-light continuum, they are further amplified in two double-pass Bethune cells separated by saturable absorbers to reduce ASE. The sulforhodamine 640 gain medium in the Bethune cells is also pumped by the 532-nm pulses from the GCR-4 Nd:YAG laser. There are two major reasons for amplifying pulses beyond the energy necessary for continuum generation. First, evidence suggests that by adjusting pulse energy, we can stabilize the continuum in the region of the spectrum needed to

seed the Ti:sapphire amplifiers. Second, 100-fs pulses with energies of ≈ 1 mJ can be focused to power densities on the order of 10^{15} W/cm², which is useful in many experiments without further amplification. As a result, experiments may be performed while the final stages of the laser system are under construction. Table 1 shows typical operating characteristics of the intermediate stage of the system.

Ti:Sapphire Amplification

Once stable, 100-fs pulses of white-light continuum are generated, the next step is to filter out the needed spectral region and inject it into the Ti:sapphire amplifier chain. As shown in Fig. 2, the first four stages of Ti:sapphire are pumped by the 10-Hz, 532-nm pulses from a second GCR-4 Nd:YAG, and the final amplifier is pumped at 5 Hz by the 500- to 550-nm, 5-J pulses from a Candela flash-lamp-pumped dye laser.

Prior to the first stage of amplification, the pulse energy is again <1 nJ. Following amplification by the first two stages, the pulse energy is on the order of microjoules, at which point the pulses must be temporally stretched from 100 fs to approximately 100 ps to prevent serious nonlinear beam distortion. The pulse stretcher is based on the now-standard design of Treacy,¹¹ which relies on the dispersion of diffraction gratings to stretch the pulse.

After being stretched, the pulses undergo amplification to the 1-J level in the final three Ti:sapphire amplifiers. The pulses are then temporally compressed back to the 100-fs level by a grating pulse compressor with a GVD that cancels the effect of the stretcher and compensates for GVD in the Ti:sapphire amplifiers.

Throughout the amplifier chain, relay-imaging techniques and saturable absorbers are used. The saturable absorbers reduce ASE, maintaining the high-contrast-ratio pulses produced in the continuum generator. The relay-imaging

system allows a high-quality spatial profile to be maintained throughout the amplification process. This is extremely important if the pulses are to be focused to a 10- μm -diam spot resulting in a power density of 10^{19} W/cm^2 .

Experimental Pulse-Width Measurement

The temporal width of the pulses produced by the CPM laser is monitored by the now-standard technique of background-free autocorrelation.¹² Autocorrelation involves

Figure 2. Block diagram of the entire ultrashort-pulse laser system. Blue lines represent pump laser beams. Components of the system are described in more detail in the text.

splitting the pulse and measuring the integral of the product of the two resulting pulses for various time delays between them. This is physically the same as performing a mathematical autocorrelation $A(\tau)$ of the function $F(t)$, where:

$$A(\tau) = \int_{-\infty}^{\infty} F(t)F(t - \tau) dt. \quad (5)$$

As shown in Fig. 3, one output beam of the femtosecond laser is split by a pellicle beam splitter. Each resulting pulse travels the length of its respective autocorrelator arm and is focused to spatially overlap with the other in a KDP crystal. The length of one arm is then modulated, introducing a relative time delay (τ) between the pulses prior to arrival at the crystal. When the two pulses overlap in the crystal at the proper angle to allow phase matching, a sum frequency pulse with amplitude proportional to $A(\tau)$ is produced. The time

average of the sum frequency pulses is detected by a photomultiplier tube (PMT) and recorded as a function of the length (proportional to τ) of the modulated arm by a digitizing oscilloscope. Both the photomultiplier and the associated electronics can be relatively slow, with time constants on the order of microseconds being easily fast enough for the technique to produce excellent results. The use of a PMT allows the instrument to exhibit an extremely high dynamic range, which is necessary for determining the amount of prepulse present in the pulses.

This type of scanning autocorrelator relies on the high repetition rate (≈ 100 MHz) of the CPM and, consequently, is unsuitable for measuring the amplified pulses, which have a repetition rate of only 5 Hz. However, the amplified pulses can be measured directly by a single-shot autocorrelation technique.^{13,14} A sum frequency pulse that spatially represents the temporal autocorrelation is generated by exploiting the

wave-front tilt inherent in the background-free autocorrelator. The spatial intensity profile is then imaged onto a diode array, allowing a single-shot measurement of $A(\tau)$.

Conclusions

Although a laser system capable of producing power densities of 10^{19} W/cm² has yet to be demonstrated, our ultrashort-pulse laser system should be considered as the sum of four well-understood parts: a CPM oscillator, a dye amplifier, continuum generation, and CPA in Ti:sapphire. The first three parts are well-understood, making CPA in Ti:sapphire the weakest link in the chain. A collaborative effort to understand the details of CPA in Ti:sapphire is under way with researchers at the University of California at Berkeley. Preliminary results indicate that we have no obstacles to the production of pulses with peak powers in excess of our stated goals.¹⁵

As of January 1990, the CPM laser was producing pulses of less than 50 fs. By the summer of 1990, our system will be at the stage where white-light continuum can be produced and seeded into Ti:sapphire. At this stage, the millijoule-level pulses will also be available for experiments. The entire 10-TW system should be completely operational by early 1991. We are developing target chambers and diagnostics for both the intermediate and final stages, and these components should be completed by the time beams are available for experiments. Our laser system will represent a valuable increase in the capabilities of L Division, providing state-of-the-art facilities for a broad range of experimental interests, including collaborative efforts with researchers from other divisions at LLNL and elsewhere.

Figure 3. Diagram of a typical background-free scanning autocorrelator. When the two pulses overlap in the KDP crystal at the proper angle to allow phase-matching, a sum frequency pulse is produced with amplitude proportional to $A(\tau)$.

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Dense-Plasma Studies Using Short-Pulse Lasers

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The NTES Directorate, in collaboration with the University of California at Berkeley, is constructing a 10-TW, 100-fs short-pulse laser capable of emitting laser fluences of 10^{19} W·cm⁻². The laser facility, which should be completed in 1991, should enable us to perform laboratory experiments that produce high-density plasma with electron temperature (T_e) greater than 1 keV and electron density (N_e) between 10^{23} cm⁻³ and solid density and to measure its properties. Advances that we hope to make in short-pulse laser technology and plasma diagnostic techniques are essential to our understanding of high-energy densities and short time and length scales.

Measurements

Optical lasers, like the short-pulse laser, are used in a range of atomic and plasma-physics studies. Although the studies of laser-produced plasma sources have been extensive and fruitful, they are largely limited to low-density plas-

mas, $N_e < 10^{22}$ cm⁻³. Short-pulse, high-brightness lasers should enhance laboratory investigations by creating high-temperature, high-density plasma. X-ray emission and absorption studies will test ion-plasma theories and characterize density-dependent diagnostics. With development, the short-pulse laser may produce: a high-brightness x-ray flash lamp to use as a nonlocal-thermodynamic-equilibrium (non-LTE) drive in atomic-kinetic experiments; a dense, inertially confined plasma; and a subpicosecond (100-fs to 1-ps) probe through plasma-absorption spectroscopy.

Laser-Development Considerations

Creating hot, dense plasma with optical lasers requires subpicosecond pulses. Long-pulse lasers impinging on a solid target cause a low-density ablation region with the laser-plasma interaction occurring at

the critical density $N_c = 10^{21}$ cm⁻³ for 1.06- μ m light. This interaction forms a hot, low-density plasma with large gradients in N_e and T_e , as shown in Fig. 1a. With short-pulse irradiation, however, we can heat the target prior to expansion or rarefaction. Figure 1b and c show the LASNEX-simulated evolution of a silicon plasma with an energy deposition of 400 J·cm⁻² in 200 fs. After the 200-fs irradiation, the plasma is in a hot, high-density state, which then expands and rapidly cools by heat conduction into the solid. To investigate this high-density state, we must heat the plasma and measure it before it expands significantly and density decreases.

The creation and amplification of ultrashort laser pulses requires special amplifiers and techniques. Very few laser amplifiers can produce subpicosecond pulses at high intensities. The Fourier condition implies that short-pulse lasers are polychromatic and must use a broadband laser-gain medium. The new 10-TW,

Figure 1. Simulated electron-density and temperature profiles for plasmas produced by laser irradiation of (a) 1 ns, (b) 1 ps, and (c) 0.2 ps. Long-pulse lasers interact at the critical density (N_c), creating a low-density plasma with large gradients in N_e and T_e . Short-pulse heating, however, occurs prior to expansion or rarefaction, but subpicosecond irradiation times are needed. A minimum prepulse is required to prevent pre-expansion.

100-fs laser will use a broadband Ti:sapphire gain medium¹ and will be capable of laser irradiances of $10^{19} \text{ W}\cdot\text{cm}^{-2}$. In a vacuum, these intensities will produce an electric field of 10^{11} V/cm , which can accelerate electrons to relativistic speeds in one cycle. Although the Ti:sapphire laser amplifier will support 100-fs pulses at high gain, neodymium-glass laser amplifiers are bandwidth limited to slightly below 1 ps. Titanium:sapphire also has a low spontaneous emission rate that minimizes the prepulse caused by amplified spontaneous emission in the laser amplifiers.

To maintain adequate beam quality, we must limit laser flux in the optics and laser amplifiers to about $10^9 \text{ W}\cdot\text{cm}^{-2}$. To amplify the laser pulses without reaching too high a flux in the amplifying medium, we will use a pair of gratings to separate the laser colors in time, stretching the pulse duration and reducing the peak flux by more than a factor of 1000 (Ref. 2). After amplification at low flux, the pulse will be recompressed with another grating pair to remove the chromatic dispersion.

For a short-pulse laser to produce high-density plasma, its prepulse must be low enough not to ablate the target material before the heating pulse arrives. On the nanosecond time scale, the prepulse focused energy should be limited to below 10^{-6} of the main-pulse focused energy to avoid target melting. This limit will be difficult to achieve in practice, and we may use target tamping to lessen these stringent prepulse requirements. We must also develop the diagnostics for very-high-dynamic-range laser power to measure the laser-pulse temporal profile, including its prepulse.

Future Physics Experiments

The short-pulse laser/target coupling and the heat flow into solid material will determine the plasma temperatures and ionization states that we can reach. Murnane and coworkers³ have demonstrated 160-fs heating of solid targets, achieving temperatures of 200 eV with laser fluences of $300 \text{ J}\cdot\text{cm}^{-2}$ and measured absorption coefficients of 25%. As plasma temperature increases, electrical conductivity will increase, and the absorption coefficient will diminish. Using the Drude model with electron-ion scattering only and assuming equilibrium ionization states, Murnane and coworkers estimated a 10% absorption coefficient for solid-density silicon at 1-keV electron temperature. To test models of plasma ionization and collision, we will perform laser-reflection measurements at high power and develop a 100-fs probe of plasma reflectivity as an indication of plasma temperature.

Although our simulations predict rapid thermal diffusion of heat into the solid, the diffusion models may not be accurate because the plasma scale lengths are comparable to electron mean free paths. The flow of heat in these short-scale-length plasmas is important in determining plasma volume and temperature profiles. We will experimentally examine the thermal-conduction properties of materials at high thermal gradients and may determine the temperature vs depth in the sample target from x-ray spectroscopy of layered targets or, perhaps, from high-precision timing of x-ray emission, as suggested by Falcone.³

We will use the short-pulse laser to produce hot, dense plasmas to study the effects of ion-plasma interactions and to characterize density-dependent diagnostics. In a dense plasma, atomic states are perturbed by the electron- and ion-microfield distribution. The ionization potentials of the plasma ions are lowered from the isolated atom values caused by the effects of plasma screening. The treatment of field ionization and continuum lowering is important in calculations of plasma-ionization distribution and opacity. Collisions also perturb and mix atomic states, affecting the energy, intensities, and shapes of emission lines, absorption lines, and edges.^{4,5} The collisional mixing of ionic states leads to the presence of forbidden transitions and asymmetric line profiles.⁶⁻⁹ The particle fields depend on plasma composition and density and are primary in producing line broadening and spectral-series merging, whose features are important as spectroscopic diagnostics of plasma density.

Experiments with laser-produced plasma at low electron densities (near 10^{22} cm^{-3}) have demonstrated the broadening and merging effects in the high-Rydberg series of ions having low atomic charge Z . These densities can be measured by methods other than line broadening, such as holography, to give an independent determination and, thus, to verify the ion-plasma theories. We will extend these measurements of broadening and merging to higher-density and higher- Z ions to test the ion-plasma theories and to develop and calibrate spectroscopic density

diagnostics for electron densities above 10^{23} cm^{-3} . The creation and diagnosis of solid-density plasmas would eliminate the need for independent density diagnostics. We will make spectral measurements of the plasma-emission features of high-Rydberg transitions to measure and quantify the density dependence of Stark shifts, broadening, and mixing of parity and dipole forbidden transitions. We also will attempt to isolate the high-density emission from the late-time emission of the blowoff plasma (the plasma plume that explodes from the target surface), using either a streak camera with several picosecond resolution or very-high-magnification spatial imaging restricted to the target surface or both. We would like to investigate the series merging with the continuum while varying the density by using pre-expanded plasma or by spatially resolving the blowoff plasma to nearly solid density. To understand the density dependence of ionization and recombination processes affected by continuum lowering, we will measure the plasma-ionization distribution or observe the intensity of high-Rydberg transitions, where spontaneous emission competes with ionization.

Our calculations suggest that short-pulse laser irradiation of targets should produce a bright, sub-picosecond x-ray source. Figure 2 shows the x-ray pulse generated by 100-fs irradiation of molybdenum with an energy deposition of $10^4 \text{ J}\cdot\text{cm}^{-2}$. Of the energy deposited, nearly 15% is radiated in broadband

x-ray radiation. Bright, subpicosecond x-ray pulses can be used for many applications: to produce photodriven x-ray lasers; to create dense, inertially confined x-ray-heated plasma; and as a non-LTE driver in atomic kinetic experiments and a subpicosecond backlighter for measuring the opacity structure of subpicosecond plasma. We will measure the emission brightness of laser-irradiated solids in this context.

Diagnostics

Although the rapid quenching of the high-density plasma emission may make time- and space-integrated diagnostics meaningful, eliminating the effects of time- and space-dependent temperature gradients will be difficult. High space and time resolution will probably be required to isolate the effects of high density. Current broadband x-ray diagnostics, capable of

recording plasma-emission spectra, cannot achieve subpicosecond resolution. A streak camera with temporal resolution of several picoseconds has been demonstrated,³ and development of subpicosecond streak cameras should be possible in the future.

We will use a similar camera to discriminate against late-time plasma emission and may use pulse-probe measurements of plasma reflectivity and color shifts of 100-fs laser light from expanding plasma to characterize plasma temperature and density. However, these diagnostics are model dependent. Two other possibilities include using (1) the subpicosecond x-ray emission from one plasma to probe absorption in another and (2) the short-pulse laser, on a 100-fs time scale, to dynamically modify efficiency or diffraction properties of crystal or grating to achieve

100-fs gating of spectra. In addition, we are investigating shadow microscopy for use in high-resolution imaging to resolve target-surface emission from blowoff plasma.

Conclusion

The advance of short-pulse laser technology will allow us to create hot, solid-density plasmas within the laboratory. The extremely short scale length and duration of these plasma sources and the high plasma densities will challenge experimentalists and theorists. The data from our experiments will help us understand the high-density ion-plasma features needed to calculate opacities, line shapes, and atomic-kinetic processes at high density as well as the theories of diffusion in high-gradient plasmas.

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Figure 2. Predicted x-ray power emitted from a molybdenum target irradiated with 10^{14} J/cm² in 100 fs. The x-ray pulse is between 100 fs and 1 ps in duration. X-ray flash lamps may be used to perform non-LTE atomic-kinetic experiments at known density and as a subpicosecond backlighter for plasma-opacity measurements.

Proposed Upgrade to Janus Laser System

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The Janus laser was built by Y Division in the early 1970s. This laser was converted into a user's facility in 1983 and has been upgraded over the years. L Division has been managing the laser since 1986. In its present configuration (Fig. 1), the Janus laser produces from 30 J (in 100 ps) to 100 J (in 1 ns) at 1064 nm in each of two beams. Either beam can be converted to the second harmonic for experiments. Provisions were made to split one of the beams and separately amplify it to a few millijoules, to convert this beam to the third or fourth harmonic, and to use it as a probe beam. Any or all of the three beams (two main beams and probe beam) can be delivered to either of two target chambers located in adjoining rooms.

We have used the Janus facility to develop new diagnostics, test current diagnostics, simulate high-altitude nuclear explosions, study population-inversion mechanisms in laser-produced plasmas, and investigate microwave switching, among other applications. We are now interested in upgrading Janus to a facility that can deliver >250 J in 1 ns in each of two beams and to provide a separate 1- to 20-ps probe beam for interferometry and x-ray backlighting. The upgraded facility would be able to compress pulses in one or both of the main beams to a pulse duration of 1 to 20 ps.

Our interest in an upgraded system arises from several considerations. The Chroma laser at KMS Fusion (Ann Arbor, Michigan) has been shut down. Our upgraded Janus facility will allow us to conduct experiments that were previously done at KMS. The 1- to

20-ps capability will provide a facility in which x-ray laser experiments can be conducted. In addition, our upgrade to a facility that can deliver 100-TW pulses to a target in 1 ps will open new areas of laser-plasma physics. Finally, the higher energies and peak powers that will be delivered by the laser to a target will provide higher x-ray flux and line radiation of higher energy than were previously possible. Such improvements will extend the use of Janus as a calibration and test facility.

Upgraded Janus Facility

At present, we are still resolving some important issues with respect to the design of our upgraded laser facility. For example, a phosphate-glass amplifier system is more efficient and produces more energy than one of silicate glass but also is more expensive. If we can obtain more space in Building 174, we can build a facility with four large target areas. However, if we are constrained to use the space we presently occupy, then only two small target areas are possible. Although these matters must still be decided, we can present a possible laser design and compare that design to the Janus laser as it now exists.

The laser we envision would cost \$2.5 to 3.5 million and would require approximately 9 months to implement. Figure 2 shows the proposed upgraded laser as it would fit into the space now occupied by Janus. Several differences between the laser systems are immediately evident. The proposed laser has more components, and output components in the proposed device are twice the

diameter of those now in use. The proposed device has four oscillators compared with three in the present laser, and the oscillators would be closer to the target rooms.

More components are required to produce a third, separate beamline, shown on the left of the oscillator/preamplifier table in Fig. 2. This pulse-compressed beam would produce pulses of 1 to 20 ps injected into the larger-diameter amplifier chains for further amplification. The output components would be capable of amplifying a 200-mm-diam laser beam compared with the 100-mm beam now delivered by Janus. The fourfold increase in area results in 400 J/beam compared with the 100 J/beam Janus now delivers. Three separate beamlines and an alignment laser are shown in Fig. 2, whereas Janus has two beamlines and an alignment laser at present. The arrangement of the proposed laser was dictated by the size of the laser room; however, the proximity of oscillators to the target areas results in earlier triggers from the laser to target-area equipment.

Several less-obvious design changes arise from our proposed design as well. For example, the 200-mm disk amplifiers shown in Fig. 2 are mounted on either side of optical tables set on edge to fit into the Janus laser room. The 50-mm rod amplifiers and 200-mm disk amplifiers are double-passed. This results in more gain at the output of the laser and fewer components on the oscillator/preamplifier table. The double-pass disk-amplifier chains are folded vertically to fit into available space. In addition, the

pulse-compression diffraction gratings used to produce a 1- to 20-ps probe beam are mounted above the oscillator/preamplifier table to save space.

Summary

Our planned upgrade of Janus will provide the following advantages over the present laser system:

- Output energy of 400 J/beam rather than 100 J/beam.
- An independent probe/backlighter beam of 1- to 20-ps pulse duration rather than the split-off probe beam.
- Pulse compression of either or both main beams to 1 to 20 ps.
- More gain at larger diameters, which reduces the possibility of optical damage to components.
- The possibility of delivering beams to four target areas if we acquire additional space.

Figure 1.
The present Janus laser. In its current configuration, this system produces from 30 J (in 100 ps) to 100 J (in 1 ns) in each of two beams.

Figure 2.
The proposed Janus laser upgrade. This system is designed to produce 400 J in 1 ns from each of two beams and to have the capability of pulse compressing both beams to 1 to 20 ps.

XUV Spectroscopy for Direct Temperature and Density Measurements of Exploding Foils

P. T. Springer

Knowledge of the x-ray absorption properties of hot, ionized plasma in local thermodynamic equilibrium (LTE) is important in understanding weapons physics and stellar astrophysics. Many plasma properties are affected by opacity, including coupling and flow of radiation through plasma, plasma dynamics, and plasma emission. Opacity models are complex to produce and require a knowledge of atomic energy levels, oscillator strengths, atomic-level populations, line-shape theories, and effects of ion-plasma interactions. Simplifying approximations must be used because computer space and time are limited and the nature of the many-body ion-plasma interactions is insoluble.

In FY 1989, in a series of laboratory experiments to test and develop our theoretical understanding of LTE opacities, we used the Nova laser to produce hot, dense plasma and to measure its opacity. However, our experiments were deficient in three ways: (1) We could not characterize the plasma accurately enough to make detailed comparisons between experiment and theory; (2) we could not obtain proof that LTE plasma conditions prevailed; and (3) the energy range that we explored was not relevant to radiation-transport calculations. By extending our measurement techniques into the low-energy x-ray and extreme ultraviolet (XUV) regions, we will see the plasma emission and correct these deficiencies.

Overview

In FY 1989, we used point-projection spectroscopy to measure the 1.3- to 2.5-keV transmission of x-ray-heated, exploding-foil opacity samples with temperatures near 70 eV (Ref. 1). The experiments yielded high-quality measurements of plasma opacity. However, because we lacked a direct method to measure the electron temperature and density of actual plasma samples, we had to rely on indirect methods that depended on complex models for interpretation and that, therefore, sacrificed accuracy.

High-quality opacity data alone are not sufficient to compare against theory. Unambiguous measurements of plasma density and electron temperature are also important. When we compare opacity data to models that use different approximations of the true atomic and plasma processes, even a small uncertainty in plasma temperature can obscure the differences between the opacities we predict.

Although we observed evidence of plasma emission in the high-energy x-ray region, where FY 1989 measurements were made, the measurements were not time resolved and were dominated by non-LTE fluorescence, making direct spectroscopic determinations of density and temperatures impossible. In FY 1990, we will implement spectroscopic diagnostics in the XUV region to directly observe plasma emission and minimize modeling ambiguities.

The condition of LTE must be satisfied to compare data with LTE opacity models. Non-LTE conditions are associated with rapid changes in plasma conditions, insufficient collision-response time, temperature gradients, low density, and non-Planckian x-ray driving spectrum, all of which are present to a degree in the plasma we create. LTE conditions are tested with Kirchoff's laws, which relate emission to plasma absorption. Our FY 1989 experiments failed to test LTE conditions because, in the high-energy x-ray region that we explored, the emitting states had very small thermal occupation and could not be observed. In FY 1990, we will use Kirchoff's laws to measure LTE conditions in the XUV region, where emission will be bright.

We also hope to obtain opacity data relevant to the determination of Rosseland and Planck mean opacities used in radiation-transport calculations. These calculations will determine the average distance that an x ray travels between points of emission and subsequent reabsorption. The x-ray region most important for these calculations is above the peak of the blackbody emission. For the 70-eV plasmas, these x-ray energies are found in the XUV region.

FY 1989 Opacity Experiments

In the FY 1989 opacity experiments, we indirectly heated a thin foil using eight beams of the Nova laser. The sample was heated and

ionized rapidly. Shortly after we fired the heating laser and the plasma sample had expanded many times its initial width, we backlit the plasma using a short burst of x rays from two other Nova laser beams. Next, using a crystal spectrometer, we measured the high-energy spectrum of the backlit x rays after they passed through the opacity sample and along its side. We compared the direct and attenuated backlit spectra, which gave us a direct and model-free measurement of the plasma attenuation.

The high-energy excited states that we probed with a spectrometer in the x-ray region had small thermal occupation, so direct emission from the sample was weak. Because the observed x-rays come mainly from backlighting, which is short in duration, we can apply time-integrating diagnostics and still probe the plasma opacity with high temporal fidelity. The advantage of the high-energy x-ray measurements is that the diagnostics are simple. The disadvantage is that the opacity and the details of the high-energy spectrum are not directly relevant to calculations of radiation transport. The excited states that we probed differed from the thermally occupied states by the addition of a relatively deeply bound inner-shell vacancy that altered the atomic structure and the possible excited-state decay mechanisms. The natural lifetimes of the excited states were shortened by Auger or Coster-Kronig decays, broadening the excited-state widths. We did not have sufficient spectrometer precision to resolve the linewidths, so the broadening affected the data interpretation.

Determination of Electron Temperature

Because electron collisions dominate the atomic-kinetic processes of low-Z ions, plasma-electron temperature is more important than radiation temperature in determining atomic-level populations. The rates for collision processes exceed the rates for radiative processes by more than an order of magnitude for the conditions achieved. The opacity and charge-state distribution are strong functions of the electron temperature. Therefore, accurate electron-temperature measurements are essential. Without them, the range of possible theories is too extensive for precise comparisons with data. Figure 1a and b compare predictions of the opacity of aluminum at a density of 0.01 g/cm^3 and temperatures of 70 and 60 eV, respectively. For a 14% decrease in electron temperature, the Rosseland mean opacity increases by 72%, and certain details of the multifrequency opacity spectrum change by a factor of 5. We derived the sample temperature using indirect measurements of the sample radiation drive and the assumption that radiation and electron temperatures are closely coupled. The radiation and electron temperatures can differ if temperature gradients exist within the enclosure or if the radiation temperature changes faster than the sample response time.

We determined the radiation temperature based on absolute measurements of wall-emission intensity, using a combination of several broadband Dante channel measurements of x-ray intensity.² We performed measurements on auxiliary

shots in a different geometry and without the use of a sample.

Therefore, we had to use models to determine the differences between the wall and sample drives.

Dante data can be interpreted to yield either brightness or color temperatures. To determine the brightness temperature, we equate the measured total fluence of x rays to the fluence of a blackbody emitter of equivalent area. To calculate the absolute fluence for the brightness temperature, we must have absolute intensity calibrations in the XUV region and knowledge of dynamic hole closure to determine the effective emitting area. The x-ray instrumentation "views" the wall emission through a hole in the enclosure, which reaches a high temperature, causing materials to blow into the line of sight and resulting in spurious absorption and emission.

To determine the color temperature, we fit the shape of the measured spectrum to an equivalent blackbody spectrum. The color temperature interpretation requires accurate relative-intensity calibrations and knowledge of the energy dependence of the hole transmission, with the highest energy channels having the least corrections. The derived temperatures based on these interpretations have differed in our experiments by as much as 20%. We attribute this difference to experimental uncertainty or to a non-LTE radiation drive.

In FY 1990, to provide a direct determination of the sample electron temperature with an accuracy of about 2%, we will make time-resolved measurements of the sample free-bound-continuum emission. In radiative recombination, which

Figure 1. (a) Prediction of aluminum opacity (κ_V) at a temperature of 60 eV and a density of 10^{-2} g/cm³. (b) Prediction of aluminum opacity at a temperature of 70 eV and a density of 10^{-2} g/cm³. Although the difference in model temperatures was only 10 eV out of 60 eV, the difference in the mean opacities was almost a factor of 2. Because opacity depends strongly on temperature, it must be determined accurately.

produces the free-bound continuum, a free electron makes a transition into a bound level of an ion, emitting an x ray. With slight atomic corrections, the x-ray spectral distribution is determined by the electron-energy distribution, which is specified by the electron temperature. Although the intensity of the free-bound-continuum emission depends on the plasma density, temperature, and ionization state, the spectral shape depends on the electron temperature. The free-bound-continuum intensity falls approximately exponentially with increasing x-ray energy. The electron temperature will be the main determination of the falloff, but the plasma optical depth vs energy affects falloff as well. The spectral distortions caused by plasma optical depth are measured independently and, therefore, will not influence the derived temperature.

Because the sample temperatures are low, we will measure the free-bound-continuum spectra using XUV spectroscopy. The recombination emission is too weak to be observed in the x-ray region because the deeply bound levels are almost completely occupied. We will carefully measure the relative efficiency of the spectrometer but will not need absolute calibrations. In addition, the sample need not be in equilibrium with the radiation drive to determine the electron temperature.³

By directly measuring the electron temperature, we can perform opacity measurements on high-density samples, which were impossible when we used indirect measurements. When the sample density is high, heating is complex and depends on the radiation spectrum and intensity at the sample position, which depend, in turn, on the temperature gradients within the

closure. Dante data will accurately indicate the radiation temperature at the sample position only when thermal equilibrium between electrons and radiation is established in the enclosure and the gradients disappear. While the enclosure is reaching equilibrium, the sample will always expand to a low density. However, by directly measuring the electron temperature, we can measure opacity well before thermal equilibrium is established. If the plasma is dense and the collision rate is high, the samples could have an LTE population distribution characterized by the sample electron temperature even if the radiation drive is non-Planckian and the heating is complex.

Determination of Plasma Density

Before FY 1989, we could only derive sample density from complex models of their hydrodynamic expansion, using either calculated or measured driving spectra. Our FY 1989 measurements of hydrodynamic expansion, using a 22 $\times$ microscope, provided the first data to compare with our calculations, although we did not image an opacity sample directly. Instead, we heated a thicker sample in a different configuration and observed its expansion using a diffuse backlighter and an x-ray microscope. We predicted sample expansion using LASNEX with the Dante data as a temperature-driving source. The predicted and observed sample expansions differed by a factor of 2, implying that the Dante temperature data do not directly reflect the sample conditions. The results suggested that the temperature vs time of the sample depends on the sample's position and orientation and that directly measuring the density of the opacity sample is, therefore, important.

In addition to directly imaging sample expansion, in FY 1990, we plan to implement spectroscopic density diagnostics using line ratios and line shapes. Line shapes depend on density produced by Stark broadening, which is caused by the interactions of the bound electrons with the fluctuating microfield from nearby ions and electrons. We will perform line-shape measurements to constrain the sample density. In LTE, line intensities are determined solely by sample density and temperature. With an accurate temperature measurement and proof that LTE conditions prevail, we can also determine the sample density using measurements of line-intensity ratios, giving added confidence to our knowledge of the sample conditions. Besides their use as a density diagnostic, linewidths and shapes are important components of opacity calculations.

Spectroscopy of high-energy x rays has not resolved linewidths that exhibit Stark broadening. For the Rydberg levels we observed with spectrometers, the broadening was less than the spectrometer resolution. Interactions with the outer-shell electron dominate Stark broadening in high Rydberg lines, whether the transition is to the K, L, or M shell. Because the x-ray energies in the L- and M-shell transitions are less than the x-ray energies in the K-shell transitions by factors of 4 and 9, respectively, less spectroscopic resolution is required to observe them. Thus, we will use an XUV spectrometer with a 22 $\times$ microscope to directly measure the density dependence of line-broadening mechanisms.

To perform these tasks, we are constructing an imaging XUV spectrometer to operate in the range of 30 to 500 eV and an imaging soft x-ray spectrometer to operate above 500 eV. We will use a

Figure 2. Schematic of a grazing-incidence, XUV flat-field spectrometer. The instrument has x-ray optics that spatially image plasma-sample emission and backlighter x rays that pass through and to the side of the sample. Spectra are recorded on a gated microchannel-plate (MCP) detector with 200-ps precision.

grazing-incidence, XUV flat-field spectrometer with x-ray optics to spatially image the sample emission on a two-dimensional, gated microchannel-plate x-ray detector. As shown in Fig. 2, this instrument has an imaging magnification of 5, with the image of the opacity sample in focus on the detector plane. The backlighter is placed a fixed distance behind the opacity sample and is imaged by the same instrument. Because the image of the backlighter converges in front of the detector plane, we will distinguish the x rays that pass through and to the side of the sample by their

spatial position. We also will separately resolve the sample emission and background spectra.

In FY 1989, we began to develop techniques to extend measurements into the low-energy x-ray and XUV regions, to achieve improved plasma characterization and determine the opacities important in radiation-transport calculations. These techniques should provide better plasma characterization, a determination of LTE conditions, and opacity measurements in the XUV region, which determines the radiation transport. The information concerning plasma emission and absorption that we

expect to gain in FY 1990 through further use of XUV spectroscopy will help us compare opacity data to theory.

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Microwave Pulse Compression and Laser-Induced Plasma Switching

P. R. Bolton and D. E. Ivie

In recent years, LLNL researchers have investigated high-power microwave interactions with matter, using pulse sources with durations from a few nanoseconds to microseconds or more. Our concern has been the development of high-power, ultrashort microwave pulse sources. Such intense pulses can be used in atomic physics, plasma physics, and electro-optics research. Research with very high microwave fields often requires cavities to build up to needed field levels. The time required is proportional to the cavity Q factor and can be prohibitively long. Experiments would benefit from having single microwave pulses that reach required field levels within a few cycles (1 to 2 ns)

and, unlike a cavity, involve only a single pass through an interaction region, affording distinguishable incident, reflected, and transmitted diagnostics.

The microwave pulse compression cavity (MPCC) provides us with a source of ultrashort pulses at repetition rates below 2 pulses/s. We use the term "ultrashort" because the pulse widths near 4 ns constitute about 11 microwave cycles and represent a large fractional bandwidth. The single-cavity MPCC device is a result of several years of development at LLNL.¹⁻³ The subject of this report is our effort to develop a versatile multiple-cavity pulse compression system with increased output power and repetition rate

and with improved timing and amplitude control.

In one phase, we studied the concept of a multiple pulse compression cavity by operating a double MPCC system. One goal was to use the output from each cavity to demonstrate phase control and optimization of net gain by coherently combining the two outputs. The multiple-cavity system is also a feasible way to distribute peak power to more than one cavity where a given field level may be too high for a single device. In the double-cavity case, the second, parallel cavity can also be used passively to further suppress leakage or prepulse energy from the single operational cavity. The multiple-cavity configuration

provides inherent experimental flexibility by selecting cavities to be operated with a versatile switch and by providing multiple pulse capability.

In a second phase, we are studying the design characteristics for laser-induced plasma switching in the MPCC. Threshold laser-pulse energies for a given optical configuration can be used to specify the number of plasma switches that can be triggered in multiple-cavity operation. We anticipate that laser-induced switching in the presence of high microwave fields should result in increased repetition rate for an MPCC, reduced jitter, and faster, more efficient switching of microwaves because of increased preionization levels.

Microwave Pulse Compression Cavity

Microwave pulse compression is achieved by dumping the stored energy of a single-mode cavity, as shown in Fig. 1. High-pressure SF_6 is used in the cavity to sustain high microwave fields. Energy dumping is accomplished by inducing an abrupt change of microwave impedance.¹ This requires the rapid closure of a plasma switch, which can be referred to as a "de-Q" or spoiler switch. The energy-storage state refers to the filling phase prior to triggering this switch.

The incident, reflected, and transmitted (output leakage) pulse powers that characterize a cavity state are monitored with fast-diode envelope detectors. Transmitted leakage is the source of prepulse energy that precedes the arrival of the triggered, intense microwave pulse.

For the tuned cavity, a return-loss resonance appears about the resonant frequency, and leakage must be minimized here. In the time

Figure 1. Single pulse-compression cavity with (a) plasma switch open for energy-storage state and (b) plasma switch closed for energy-dumping state.

domain, the reflected power signal resembles a characteristic fill curve (see top trace of Fig. 2). The bottom trace of Fig. 2 shows the development of leakage energy for the same input pulse duration. During the incident pulse (of peak power P_0), the reflected power is an exponentially decaying function, as follows:⁴

$$P_r(t) = P_0 - \left(\frac{P_0 4\beta}{(1 + \beta)^2} \right)$$

$$\times \left\{ 1 - \exp \left[- \left(\frac{1 + \beta}{2\tau_0} \right) t \right] \right\}$$

$$\times \left\{ 1 + \beta \exp \left[- \left(\frac{1 + \beta}{2\tau_0} \right) t \right] \right\} \quad (1)$$

The intrinsic time constant τ_0 is equal to Q_0 , the intrinsic cavity Q divided by the angular microwave frequency ω . The value of Q_0 is limited by internal losses and leakage. The parameter β is a measure of cavity coupling to the external world. When the cavity is tuned to the critical case ($\beta = 1$), reflected power diminishes to near zero within a few time constants. Stored energy then builds up as follows:

$$U(t) = \frac{4\beta P_0 \tau_0}{(1 + \beta)^2}$$

$$\times \left\{ 1 - \exp \left[- \left(\frac{1 + \beta}{2\tau_0} \right) t \right] \right\}^2 \quad (2)$$

Figure 2. Pulsed diagnostics for the tuned pulse compression cavity. (top) Reflected power for critical coupling. (bottom) Corresponding transmitted leakage power. Signals are negative voltages.

Figure 3. Typical output pulse shape for a single pulse compression cavity. Signals are negative voltages.

After a few time constants, the stored energy is near its asymptotic value. The plasma switch is then fired at time t_c , abruptly transferring the pulse compression cavity from a storage to energy-dumping state. Stored energy is dumped within a time interval comparable to the transit time for microwaves across the cavity. Figure 3 shows a typical output pulse shape.

The active component of the MPCC is a gaseous plasma switch, which consists of a gas volume confined inside a quartz tube within the cavity. A triggered dc spark gap has been the typical trigger for preionizing the switching gas. With this preionization, the high microwave field heats the free electrons and drives the gas breakdown (via a cascade process) to a density and volume where the plasma is partially reflective (near $10^{12} \text{ e}^-/\text{cm}^3$). The weakly ionized plasma is also absorptive, degrades the loaded cavity Q , decouples the cavity from the source, and by virtue of the plasma position, rapidly enhances coupling through the output port, thus dumping the stored energy. The switching process is adiabatic, requiring a few microwave cycles. The peak-power gain G is maximum for the critical coupling case. The input power level is limited by the threshold at which the microwave field itself initiates the plasma switch (self-triggering). Table 1 lists typical operating specifications for the single pulse compression cavity.

Coherent Double-Cavity Microwave Pulse Compression

If fed by splitting a single incident pulse, the outputs of multiple cavities can be synchronously combined to result in a single pulse output whose net gain is controlled by relative cavity input phases. We

have demonstrated this coherent superposition of output from two MPCCs operated in a section of waveguide.^{5,6} The two cavities were filled in parallel by equally splitting a single fill pulse, preserving phase coherence. A high-power phase shifter was placed before the input port of one cavity.

Each cavity was critically tuned to the same resonant frequency. MPCC1 and MPCC2 refer to pulse-compression cavities 1 and 2, respectively. Because the intrinsic Q values were different (8500 for MPCC2; 11,450 for MPCC1), peak-power gains also differed for individual outputs.

With both cavity outputs overlapped in time, the output from MPCC2 was phase-shifted by the input phase shifter to maximize the peak power (electric field) at 131.8 kW (3435 V/cm). Figure 4 shows the individual cavity outputs (top trace) and the combined pulse (bottom trace). Continued phase shifting by another π radians yielded a minimum output power (electric field) of 3.6 kW (568 V/cm). Therefore, we could vary the peak power output and net gain over a 16-dB range by input phase control alone. This is the contrast ratio. Given the individual peak fields, $E_1 = 1999$ V/cm and $E_2 = 1534$ V/cm, these extrema agree (within an experimental error of 18% in power) with the expected algebraic field limits imposed by vectorial superposition, where $E_{\max} = E_1 + E_2$, and $E_{\min} = E_1 - E_2$. Individual cavity outputs must be matched to achieve the highest contrast ratio, with $E_{\min} = 0$. This coherent operation has more recently been demonstrated at the 34-MW level with a 10-dB contrast ratio.⁶

We also demonstrated field redistribution in the double-cavity system. That is, for a fixed input power,

the peak electric field in each of N cavities would be reduced by the factor $N^{1/2}$ compared with that for the single-cavity case. For a required high-field output, each cavity in a multiple system could operate at a more stable, reduced field level.

Table 1 shows that a single-cavity MPCC is characterized by suppression of the prepulse (transmitted leakage) down to -55 dB with respect to input power. We further suppressed this leakage by at least an additional 20 dB using the second cavity of the double MPCC system as an inactive one (plasma switch not triggered).⁶

An interference technique can be used because the leakages are coherent. With a two-cavity interference approach, the phase difference between the two long pulse leakages (prior to firing one cavity) is adjusted until there is destructive interference at their combined output.

Prepulse levels as low as -85 dB with respect to the input level have recently been observed. With respect to peak power output, the prepulse is then suppressed to the -85-dB +G level, which can exceed -100 dB (for moderate gain, with G in excess of 15 dB).

Figure 4. Output for double pulse compression cavity. (top) Individual single-cavity outputs. (bottom) Coherently combined output in-phase. Signals are negative voltages.

Table 1. Operating specifications of a single microwave pulse compression cavity.

Parameter	Specification
Peak power gain G (dB)	20
Maximum peak-power output (MW)	~150
Maximum electric-field output (V/cm)	10^5
Output mode	TE ₁₀
Maximum repetition rate (pulses/s)	2
Output pulse duration, FWHM (ns)	4
Output pulse rise time (ns)	1-2
Timing jitter (ns)	2
Relative prepulse level (dB)	-75
Input threshold for self triggering, 1- μ s input (MW)	~1
Resonant frequency (MHz)	2860
Energy storage efficiency (%)	35
Intrinsic cavity Q	10,000
SF ₆ tuning characteristic (kHz/psi)	-204

A generalized multiple-cavity system is easily visualized. The added cost is the increased complexity of multiple cavities and the required multiple plasma switching. Simple plasma switches, which can be triggered by a versatile multichannel trigger, are needed. The laser-induced switch can provide multiple-cavity operation with reduced timing jitter and greater timing control with higher repetition rates.

Laser-Induced Plasma Switching

Laser-induced gas breakdown near threshold provides localized, high-level preionization to initiate the microwave impedance switch in a cavity. Although ionization levels locally exceed the microwave critical density by orders of magnitude, the effect on microwaves is limited by the spatial confinement of plasma near the laser focus. In fact,

low-field microwave interferometric data confirm that the plasma becomes absorptive early in the afterglow phase as it expands. Gases are used to maximize microwave-field holdoff capability. Low pressures (≤ 1 atm) are used for convenience of multiple-switch design.

One goal in our studies was to measure laser-pulse thresholds for breakdown of various gases near atmospheric pressures at wavelengths of 1064 and 266 nm. Another goal was to observe the effect of such preionization on low-field microwaves. For a given optical configuration, we can determine pulse-energy requirements for simultaneously triggering many parallel cavities. Threshold results represent upper limits when applied to a high-microwave-field bias.

We focused laser irradiation into a suprasil tube inserted through a section of WR284 waveguide. The synthesized frequency resolution of the 2860-MHz probe was 100 Hz. Figure 5 shows the experimental configuration. The interferometer used a Mach-Zehnder configuration and included a double pass (not shown) through the plasma region to increase sensitivity.

Because we are concerned with the high-field operation of a repetition-rated microwave device, laser-breakdown thresholds were defined for a 5-pulse/s repetition rate with injection seeding. Threshold levels were taken to be those for which recombinant light emission was detected by a photomultiplier tube with every pulse. Our interest is in gases, such as SF_6 , nitrogen, and argon, which can sustain high microwave cavity fields for required times.

Figure 5. Exemplary configuration for studies on laser-induced breakdown in gases monitored by S-band microwave interferometry.

Figures 6 and 7 show laser-pulse-energy thresholds for induced breakdown with 1064-nm light. In these cases, ionization proceeds mostly via a cascade process with an effective ionization rate ν_i defined by:

$$n_e(t) = n_e(0)e^{\langle\nu_i\rangle t}, \quad (3)$$

for n_e as the time-dependent free-electron number density. In the cascade regime, there is typically an inverse pressure dependence for the breakdown threshold, as seen in the figures.

Direct ionization of SF_6 facilitates simpler switch design without the need for isolated gas volumes in a cavity. A 1064-nm laser pulse energy of 780 mJ is sufficient to preionize simultaneously (trigger) SF_6 plasma switches of at least ten pulse-compression cavities. The intensity threshold for breakdown of SF_6 can be compared with results obtained by Hargis,⁷ where breakdown intensities near 10^{10} W/cm^2 were measured for 1000 Torr. The microwave interferometer monitors the plasma effect on phase and field amplitude during the afterglow. Table 2 lists typical results for some gases. Amplitude reductions (ΔA) are early maxima accompanied by the listed phase changes ($\Delta\phi$). Absorption of microwave energy by the preionized volume represents the initial step for an impedance switch driven by a high microwave field. Note that SF_6 at threshold shows no significant microwave effect at early times (because of the rapid electron attachment rate to the form SF_6^-).

Early microwave effects are clearly observable when the SF_6 pressure is reduced, when a large admixture of air is introduced, or when a plasma is formed by applying laser intensity well above breakdown threshold. For all cases

studied, microwave effects are enhanced when the laser intensity exceeds the threshold value. In several cases, comparisons of incident and transmitted laser pulses show the onset of pulse tail erosion as a result of the rapid growth of

electron density during the pulse. This result suggests that local electron densities approach critical levels for 1064 nm.

Interferometric results in a waveguide can be processed to obtain time-dependent, spatially averaged

Figure 6. Laser-pulse energy thresholds for breakdown of argon, neon, and helium with 1064-nm irradiation at 5 pulses/s.

Figure 7. Laser-pulse energy thresholds for breakdown of laboratory air, N_2 , and SF_6 with 1064-nm irradiation at 5 pulses/s.

microwave conductivities.^{8,9} From the real part of the averaged conductivity, we can estimate an averaged electron number density, as follows:⁹

$$\langle n_e \rangle(t) = \frac{m_e}{e^2} v_r \left(1 + \frac{1}{F^2} \right) \times \omega \epsilon_0 \frac{\lambda_g^2}{\lambda_g^2} (0.115) \frac{\Delta A}{2\pi l} (1 - \theta), \quad (4)$$

where

$$\theta \equiv \frac{\Delta \phi \lambda_g}{360(2l)}, \quad (5)$$

and

$$F \equiv F(\lambda_g, \Delta A, \Delta \phi, 2l) = \frac{v_r}{\omega} = C. \quad (6)$$

The electron mass is m_e ; e is the electron charge; and ϵ_0 is the vacuum permittivity. The average electron momentum alteration rate is v_r ; λ_g is the guide wavelength; $2l$ is twice the plasma thickness along the microwave propagation direction; and F is an experimentally determined ratio equal to the collisionality C . For example, the 1-atm case for argon in Table 2 yields $n_e \approx 10^{15}/\text{cm}^3$ and $v_r \approx 10^{11-12}$ in early afterglow. Because plasma partially fills the waveguide cross section, a time-dependent enhancement or filling factor must be included to determine local electron densities.

It is no surprise that the microwave interferometer shows that the laser plasma afterglow can endure beyond 100 μs . However, the recovery time in the presence of high microwave fields will determine the operational repetition rate of a pulse compression cavity.

Our study was conducted without high-microwave-field biasing. In a high-field cavity environment, relatively few seed electrons are needed to initiate a microwave-driven ionization of the switching gas to the absorptive and reflective state. Consistent with Eq. (3), the higher laser-induced preionization can reduce the microwave switching time. The high microwave field may also reduce the laser-breakdown time because of its greater efficiency for electron heating.

We are now investigating breakdown thresholds and interferometric observations for 266-nm irradiation with the same experimental configuration. Laser-induced preionization can be considered with several types of configuration, wavelength, and pulse characteristics. We have obtained new results for microwave switching (also applicable to higher frequencies) with much shorter pulses (120 ps) and higher pulse energies (near 1 J) using 1064-nm light. Coupling of low microwave fields into the plasma is more rapid. Furthermore, the use of higher-

power laser pulses permits expansion of the focal region (preionization volume) for more efficient, prompt switching action.

An alternative preionization scheme proposed years ago involves using a pulsed or continuous-wave (tunable) laser to selectively excite alkali atoms. The alkali content need only be a few parts per million in the switch. Tunable excitation to principal levels, which can be field-ionized at microwave frequencies, represents a useful, programmable aspect of plasma switching in a microwave cavity or any high-field device.

Summary

Multiple pulse compression cavity systems are feasible and have various applications. Phase control of output pulses from each cavity allows synchronous, coherent combination of multiple-cavity outputs with optimization of the net gain and gain control specified by a contrast ratio. For a given required output, field distribution allows each cavity of the system to operate more stably at peak fields reduced with respect to a single-cavity device. Furthermore, selected component cavities can be rendered inactive for the purpose of greatly enhancing prepulse suppression by an interference technique. In a multiple configuration, cavity lengths can be varied to produce interesting pulse shapes. The design of such systems relies critically on commensurate development of a suitable plasma switch. Appropriate switching-gas candidates should be characterized by the ability to sustain high microwave fields for long periods in the absence of preionization, relative ease of laser-induced breakdown, and minimum afterglow plasma recovery times to improve repetition rates. In a high-field cavity, the

Table 2. Microwave interferometry of early afterglow at threshold intensity.

Gas	Pressure (Torr)	Amplitude change, ΔA (dB)	Phase change, $\Delta \phi$ (deg)
Argon	760	7.1	59
Argon	60	12.2	41
SF ₆	760	0	0
Air	760	0.4	2
Neon	760	12.2	145
Neon	351	12.7	156

coexistence of two, intense fields differing by about five orders of magnitude in frequency, each capable of driving gas breakdown to their critical electron densities, leads to expectations of low-jitter, efficient, rapid plasma switching.

Many generalizations can be made in developing these pulse sources. Cavities can include a broad range of frequency, length, media, and geometry. Laser pulses can include different wavelengths, pulse widths, energies, and focusing properties. Our research also has applications to gaseous electronics, electro-optics, high-power microwave systems design, and laser development.

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Laboratory Simulation of High-Altitude Nuclear Explosions

G. Dimonte and L. Wiley

The STARFISH nuclear device (~1 Mt) was fired on July 9, 1962, at an altitude of 400 km above Johnston Island in the Pacific Ocean. It produced visual effects in New Zealand 7400 km away and global artificial radiation belts that survived for 1 y and affected satellite operation. Street lights in Hawaii 1600 km away were shut down in the same way that auroral storms disrupt the Canadian power system. The bomb debris consisted essentially of an iron plasma that expanded against the earth's magnetic field ($B \sim 0.3$ G) and ambient ionospheric plasma

at a speed of $v \sim 1.5 \times 10^8$ cm/s. Calculations and in situ measurements indicate that a large diamagnetic plasma bubble was formed with an average radius of $R_b \sim 300$ km. Because the expansion velocity was comparable to the local Alfvén speed $v_a \sim 5 \times 10^7$ cm/s, magnetohydrodynamic (MHD) shocks and Alfvén waves may have been generated. Photographs of the exploding plasma exhibit a complicated three-dimensional structure, including field-aligned striations and cross-field plasma jets having the dimensions of the ion Larmor radius $\rho_i \sim 20$ km.

A nuclear event is not only catastrophic to the immediate environment but also affects distant systems because, in space, the energetic photons and particles have large mean free paths. With so many satellites in orbit and many more contemplated in the Strategic Defense Initiative, it is important to understand the many spheres of influence of a very-high-altitude nuclear explosion (VHANE).

On short temporal and spatial scales, one is concerned with the fracticide of nearby platforms

and the blinding of space-based sensors by delayed gamma radiation. The expanding bomb plasma is subject to many instabilities, which form complicated structures that can confuse even distant infrared and radar sensors. On a larger and longer scale, energetic megavolt fission fragments become trapped in the earth's magnetic mirror and form potent artificial radiation belts that survive for months and damage satellites. On yet a more global scale, a VHANE can couple a significant portion of the kinetic yield into low-frequency (~ 1 -Hz) Alfvén waves that disrupt ground-based power and communication systems. Although these effects are diverse, their influence

depends crucially on the temporal and spatial distribution of the weapon debris and energy.

The plasma effects are difficult to calculate from first principles because the interactions are nonlinear, multidimensional, and collisionless. The most comprehensive calculations employ state-of-the-art three-dimensional electromagnetic computer codes that still use simplifying assumptions because of the wide-ranging scales of the problem, such as the different (1) electron and ion masses and (2) bomb and ionospheric plasma densities. Because experiments are needed to check the validity of the modeling assumptions and nuclear experiments in space are forbidden, we are

experimentally investigating key physics issues associated with nuclear explosions in space.

Experimental Program

To simulate VHANEs in a relevant way, one must produce a compact, dense energetic plasma (simulating a bomb) in a large, tenuous magnetized plasma (representing the ionosphere) such that:

$$\rho_i \ll R_b \quad (1)$$

$$v \sim v_a \quad (2)$$

where ρ_i is the ion Larmor radius, R_b is the bubble radius, v is the plasma-expansion velocity, and v_a is the Alfvén speed. The first criterion [Eq. (1)] is important because the growth rate and scale lengths of MHD instabilities affecting the expanding plasma, such as Rayleigh-Taylor (R-T) and lower-hybrid-drift (LHD) instabilities, are determined by ρ_i/R_b . The growth rate and scale length of these instabilities will determine the eventual extent and structure of an exploding plasma and, therefore, how bomb debris will distribute spatially. The second criterion [Eq. (2)] affects how the expanding plasma interacts with the background plasma. In particular, diamagnetic currents within the bomb plasma can radiate Alfvén waves (MHD-electromagnetic pulse, MHD-EMP) efficiently when $M_a \equiv v/v_a \sim 1$. Calculating the MHD-EMP generated by the bomb plasma is formidable because the expansion is anisotropic and highly structured as a result of the plasma instabilities. When $M_a > 3$, the Alfvén wave coupling is much smaller. Instead, strong MHD shocks similar to planetary bow shocks are formed that accelerate the background ions. This in turn changes the deceleration of the

Figure 1. Schematic of VHANE simulation experiment. Two intense laser beams irradiate a spherical CH_2 target to obtain a spherical explosion. A microwave source produces a xenon plasma in a magnetic field. The structure of the diamagnetic bubble is detected with the Faraday rotation diagnostic using FR-5 glass, a polarized laser beam, and a streak camera. A framing camera is used to photograph the structure of the exploding plasma, and particle analyzers measure the energy distribution of the plasma. Radio-frequency probes measure the magnetic perturbations and the coupling to Alfvén waves. The diamagnetic loop and B-dot probe measure the magnetic-field perturbations of the ablation plasma. The magnetic-field coils produce the magnetic-mirror geometry.

bomb plasma and, hence, the R-T and LHD instabilities. These complicated symbiotic interactions are difficult to calculate confidently and must be examined experimentally.

Our current design for such an experiment is shown schematically in Fig. 1. A nuclear explosion can be simulated in the laboratory by irradiating a small (<1 -mm) plastic sphere with ~ 100 J of laser ($1.05\text{-}\mu\text{m}$) energy at the LLNL Janus facility. The resulting ablation plasma expands against a background magnetic field until the plasma and field-energy densities become comparable. The background ionosphere is simulated by a microwave discharge plasma in a simple magnetic mirror. This magnetic geometry not only facilitates the microwave transmission and discharge but also simulates the earth's dipole magnetic mirror, which confines the bomb debris. We employ a coaxial magnetron to generate 20 kW of 9.5-GHz microwave power, which is absorbed near the electron cyclotron resonance within a large (80-cm-diam, 120-cm-long) vacuum chamber.

To satisfy Eq. (1), we prefer light laser-target ions (hydrogen) and a strong magnetic field. Our initial target will be a CH_2 sphere because it is a convenient source of hydrogen. The difficulty is that it will also generate multiply ionized carbon, which may complicate the scaling in Eq. (1). To satisfy Eq. (2), we need heavy background plasma ions and a weak magnetic field. By using the massive xenon ion for the background plasma, we minimize the plasma density required to achieve a particular Alfvén speed. In

addition, the microwave discharge power is minimized because the sluggish xenon ion is better confined. Reconciling the conflicting requirements of Eqs. (1) and (2) on the magnetic field, we choose an intermediate value $B \sim 2$ kG. For our parameters, the bubble radius becomes $R_b \sim 5$ cm, and the Alfvén wavelength becomes ~ 10 cm. Because our experiment is large, we can accommodate many wavelengths within our chamber, but it will require ~ 100 kW of power to operate. The experimental parameters (assuming hydrogen for simplicity) are compared to the STARFISH parameters in Table 1. As shown, the two experiments are quite different in magnitude, yet they address similar physics issues because the dimensionless parameters ρ_i/R_b and v/v_a are similar.

We are also developing a novel diagnostic to measure the magnetic field perturbations using Faraday rotation. By line focusing a diagnostic laser beam through a high Verdet-constant glass (FR-5) rod oriented radially from the target, we will measure the magnetic perturbations in space and time simultaneously with the high bandwidth of a streak camera. With this diagnostic, we can compare the complicated structure of a critical shock directly with the computer simulation profiles. Usually, these measurements are performed at single points with more limited bandwidth. Other planned diagnostics include interferometry, ion spectrometers, Langmuir probes, electromagnetic probes, Faraday cups, diamagnetic loops, and optical imaging and spectral diagnostics.

Table 1. Comparison of STARFISH parameters with the experimental parameters.

	STARFISH	LLNL
Total plasma energy (J)	$\sim 10^{15}$	20
Altitude (km)	400	0
Number of ions	10^{28}	3×10^{17}
Atomic mass	55	1
Expansion speed (10^7 cm/s)	15	2-3
Magnetic field (G)	0.3	2000
Larmor radius (cm)	2×10^6	~ 1
Bubble radius (cm)	3×10^7	~ 5
Background ion density (cm^{-3})	2×10^5	5×10^{12}
Background ion mass	8	131
Alfvén speed (10^7 cm/s)	5	1.7
ρ_i/R_b	0.07	~ 0.2
v/v_a	3	1-2

Field Operations

2

Nuclear tests are complex physics research or weapons development experiments that, because of the necessity to contain the resulting radiation products, are conducted under unusual, challenging, and often adverse conditions. These tests are underground laboratories in which experimental measurements are made using state-of-the-art diagnostic technology that depends on the functioning of precision laboratory instruments. All of this must be accomplished in an underground environment, that is, buried and inaccessible, with all operations automatically or remotely controlled.

The Field Operations Program is the field engineering and operations management element of the NTES Directorate. Its principal mission is to ensure that underground nuclear tests and related experiments at the Nevada Test Site (NTS) are executed safely to meet the experimental objectives of the Defense Systems Program.

The technologies of several engineering disciplines form the basis for Field Operations activities, and skilled personnel are drawn from several LLNL organizations. The Mechanical Engineering Department provides mechanical, civil, and structural engineering and technical support; Electronics Engineering provides electronics and electrical support. The Nevada Test Operations Department, located at the NTS, provides additional engineering and technical support, with emphasis on construction and drilling. We also use and depend on the NTS contractor organizations for technical support in certain areas such as field inspection, as well as for the skilled craft personnel that are so vital to the successful completion of large field projects.

An underground nuclear event is a complex undertaking. Field Operations becomes involved in an event when the nature of the experiment has been defined and an

approximate execution date has been selected. We are responsible for developing and managing the operational plan for the event, including a detailed schedule that identifies the major milestones. Because many diverse organizations and disciplines must work together in a smooth and orderly manner, effective communication and coordination are essential. The test director, who is in effect the operational project manager, is the focal point for operational planning and scheduling.

We are responsible for providing a facility and field support network for experimenters to prepare and conduct experiments. The facility for an underground test is the ground zero (GZ) site, which consists of the emplacement hole, temporary support structures, surface preparations such as roads, and utilities. We design each site, write specifications for the structures, and manage and oversee the site preparation. Operational activities at the GZ site are under the control of the test director, although the responsibility for controlling daily operations is often delegated to the LLNL event mechanical engineer or the construction engineer.

A major focus for Field Operations personnel during the course of an event is coupling the nuclear explosive device to the experiment. We provide the timing, arming, and firing system, as well as the canister system in which the device is contained. The responsibility for nuclear safety (that is, ensuring that the nuclear device is not exposed to any threat or external influence that could result in its damage, destruction, or premature detonation) during the GZ operational phase belongs to Field

Operations. This responsibility includes managing and controlling the activities that relate to the device and its support systems, and ensuring that all device-related designs and procedures comply with approved criteria.

Field Operations must ensure that all activities in support of an underground test at the GZ site are conducted safely. We also are committed to conducting GZ operations in a manner that is in compliance with environmental and health regulations and laws. Quality assurance is an integral part of our planning and operational processes. We are dedicated to ensuring that all actions taken to prepare for and execute an underground test are consistent with reviewed and approved procedures.

In the Field Operations Program, we are always seeking more efficient, cost-effective, and faster methods of doing our work, either by improving an existing capability or developing a new approach. The following recent actions serve as examples.

We are developing a heavy-lift capability that will enable us to safely and reliably emplace experiments that weigh 700 tons. Our present capacity is about 400 tons. With the new Manitowoc 6000/Lampson Heavy Lift crane system, we will be able to lift up to 750 tons. Before we can safely and effectively use this capacity to its limit, we must upgrade the capacity of several elements that are critical load-bearing members during the emplacement operation. Therefore, we plan to improve the subbase platform, elevator, and linkage equipment.

The subbase platform is the work platform that provides the support

base for the downhole operation. It supports the weight of an experiment package after it has been released from the crane. This new platform will have a working capacity of 700 tons. The elevator is the gripping mechanism that provides the direct-handling interface with the emplacement pipe. The new unit will have a working capacity of at least 667 tons and will accommodate a 13.38-in.-diam emplacement pipe. A set of linkage equipment provides the transition from the crane block swivel eye and the elevator and will have a working load capacity of 667 tons.

We also have consolidated our drilling operations with those of the Los Alamos National Laboratory to reduce the overall drilling cost to both Laboratories. Each Laboratory had been using one full drilling crew for 5 d/wk. In FY 1990, we will begin to share the efforts of one crew that will operate 7 d/wk. We believe this will reduce each Laboratory's field budget by about \$4 million/y. However, we will lose about 30% of the drilling product per year, so we must manage our hole inventory with less contingency. Also, planning for the use of the drilling resource must be closely coordinated with the Los Alamos program.

With the recent trend toward more complex events and reduced budgets, we believe we must continue these efforts to improve performance and cost-effectiveness in order to ensure the long-term productivity of the program. The following articles describe some of the noteworthy developments and accomplishments of FY 1989.

VARs: A Visual Archival and Retrieval System on Laser Disc

S. P. Stark and M. E. Kinkenon

The Nuclear Test Operations Department (NTOD) Photo Applications Group originated in the late 1950s to document LLNL's Nuclear Test Program at the Nevada Test Site (NTS). During the last 30 y, the number of negatives kept on file in our group has grown to exceed 80,000. As a result, researching requests for photos on a particular subject had become difficult and time-consuming. Therefore, we devised a system, called the Visual Archival and Retrieval System (VARs), that alleviates this problem.

Our primary concern when developing the VARs was to use the selected hardware and software as part of a classified system. We also wanted to quickly store and access large amounts of optical information and corresponding data. Additionally, we required a custom software program designed to interface with the hardware and create an archival system.

Hardware

Personnel at iTeleNet Systems, Inc., of Carpinteria, California, helped select hardware and integrate it into the VARs. The hardware design of the VARs is based on laser videodisc technology (Fig. 1). The quality of our laser-disc images is more than 300 lines of horizontal resolution, and only about 30 s is needed to input an image and its associated data. A laser-disc image does not replace the actual negative but, instead, acts as an efficient archival and retrieval tool. We selected the Teac LV-210A recorder and the LV-210P player for their

analog-recording capabilities. These machines use standard 12-in. optical Teac Model 300 CAW discs that store up to 54,000 images/side. Video input can come from various sources, but we use a video camera with a positive/negative imaging capability. The positive/negative polarity switch on the camera enables us to record negatives as well as transparencies. The standard signal that we use is the National Television Systems Committee (NTSC) color-video signal.

To control the recording and duplicating process and to enter information corresponding to a given image into a data-base file, we use an IBM PS2/80 computer running at 16 MHz. A 70-Mbyte hard disc is used for data-base storage, and an IBM streaming tape drive is the backup device. We complete the

hardware configuration with an external 5-1/4-in. floppy-disc drive to install software changes along with an NEC Pinwriter/P6 printer for hardcopy output.

Software

In designing the software, we had to consider that the software would need to support approximately 110,000 entries. Laserbase 3.03, the software we chose for the VARs, runs on an IBM personal computer or an IBM clone, both of which operate under the DOS 3.0 (and above) operating system. The VARs is programmed in QuickBASIC 4.5 and dBASE III+.

Through our consultations with personnel at Rainbow Enterprises of Ventura, California, we decided to use the BASIC computer language to handle pop-up menus, user input,

Figure 1. The Visual Archival and Retrieval System (VARs).

and the Teac laser-disc interface through the IBM serial ports. The dBASE III+ computer language handles all data-base manipulation operations, including indexing, adding, deleting, and searching.

Some useful software features have been incorporated into this program. Most importantly, we designed the VARS to enable the user to input a minimal amount of information during the data-entry process. The user can also quickly enter duplicate information as well as automatically record the laser-disc frame number. Additionally, the data base handles up to seven

index fields (Fig. 2). These fields give the user a variety of search criteria, thereby permitting efficient search operations.

Of particular interest is the Splice software utility. This utility is used with Laserbase 3.03 as an editing, authoring, and recording program that serves several functions. For example, we can develop various video presentations, prepare technical reports, or group a number of similar images together for later retrieval through Laserbase. The Splice utility may also be used to copy images to another laser disc or another medium.

Future Modifications

Although it is not fully defined at this point, the VARS will be developed in a variety of ways. In terms of the software, we will change from the dBASE III+ to the Foxbase+ software program. By using the compiled version of this software, we estimate that the search speed will increase by a factor of 8 to 10. We are also considering another software modification that will enable us to record event albums onto laser disc. An event album is a collection of nuclear-test photographs for a particular event that is assembled into an indexed book. Using this software modification, we need only about 3-4 h to produce one event album. It currently takes us 160 h to assemble a complete event album because we print, label, and assemble the photographs for each album into a book. Each album (three albums are assembled for each test) must then be indexed and brought into accountability as a classified document.

Our hardware changes may include purchasing newer, high-resolution laser-disc units and a color printer capable of producing high-quality viewgraphs and prints from data-base images. We also may upgrade to a faster computer with a larger hard disc.

The screenshot shows a terminal window titled 'VIEW <1 Found>'. It contains a form with the following fields:

- Catalog # N-009435
- Location U7A
- Category ASSEMBLY
- Description DEVICE
- Subject FOREST
- Requestor STARK, D.
- Class SRD

Below this form is a table with the following data:

Reference #	Group	Media Negative	Date
Disc ID# 000001	Start-End/Filename	9732-9732	Notes

At the bottom, there is a message: 'Please Insert laserdisc ID # 000001 into one of the laserdisc units, and press [A] to view the image(s) associated with this record.' Below the message is a control bar with the following options: [ESC] - Exit, [M] - View Memo, [P] - Play 'Object', [F1] - Help.

Figure 2. The VARS screen display. Shown are the various data fields.

Performance of Transient Limiters under Laboratory, Simulated, and Rocket-Triggered Lightning Conditions

R. T. Hasbrouck, J. P. Johnson,* and J. Breitmeier†

We have designed and tested a prototype lightning-invulnerable device system (LIDS) that implements a lightning-protection method referred to as the "fortress concept." The fortress, a structure based on the Faraday cage, protects the nuclear explosive test device system by surrounding it with a continuous metallic skin. Each electrical conductor that must enter the fortress is enclosed within a cable, which is, in turn, enclosed in a metallic shield that terminates at the entry point and is electrically bonded to the outer metallic surface of the fortress. Within the fortress, each penetrating conductor is protected by a transient limiter.

We tested the LIDS by means of full-threat-level simulated lightning and actual lightning triggered by rockets. We subsequently tested several limiter components by using a laboratory-type surge generator to investigate certain seemingly anomalous responses. This paper reviews the fortress concept, discusses the operation of the limiters, and examines their performance. Explanations are offered for the anomalous responses, and several important design considerations and trade-offs are discussed.

The Fortress

The fortress provides protection against a worst-case situation in which a full-threat-level lightning

stroke attaches directly to electrical cables connected to the test-device system (hereafter referred to as the system). Protection is achieved by providing a low-impedance path—from ground to the lightning return-stroke channel—that bypasses the system. This path is achieved by bonding the cable shields to the outer skin of the fortress using

360-deg backshell, electromagnetic interference/radio-frequency interference (EMI/RFI) connectors mated to bulkhead-mounted, feedthrough receptacles. The shields are not allowed to penetrate into the fortress. Voltage transients, induced by the return-stroke current onto the system's conductors, are limited to safe levels by routing all conductors

Figure 1. Simplified diagram of the lightning fortress (LIDS). Metallic shields protect the electrical conductors, and the device system is further isolated from lightning currents by a metallic skin and transient limiters.

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through transient limiters located within the fortress and close to the entry point (Fig. 1).

In the following, the function of the fortress is explained for negative cloud-to-ground lightning (i.e., negative charge lowered from the cloud).

In general, the explanation also applies to the less-frequent (i.e., 10%) positive lightning, although the associated currents will have lower rise rates and higher peak values than for negative lightning. Initially, a conductive path is established, via

the cables and fortress, between the stepped leader and ground. Next, positive charge moves quickly from Earth to cloud, neutralizing the path's negative charge. This upward-moving charge, the high-amplitude return-stroke current, exhibits a high rise rate (di/dt) and a large peak amplitude. Large voltage transients are developed across impedances through which the current flows (e.g., the fortress skin and cable shields).

Arcing occurs at the cable attachment point, and the resulting plasma produces a short circuit between shields and conductors. This induces the transient voltages onto conductors connected to the system. However, the rapidly rising voltage quickly causes the transient limiter to go into conduction, shunting damage-producing current away from the system and holding the voltages on the conductors to safe levels (Fig. 2).

Transient Limiters

Several types of limiters (Fig. 3) are required because our system uses both coaxial and multiconductor cables for carrying fast-rise-time pulses, low-voltage dc command and monitor signals, and ac power. A limiter must present a very high impedance under normal working voltage and quickly change to a very low impedance when exposed to a large-amplitude transient.

The silicon avalanche diode (SAD) is a semiconductor, voltage-clamping device that clamps in nanoseconds. It has a nonlinear impedance characteristic (i.e., it obeys the power law, $I = KV^{\alpha}$) and functions as a shunt-connected zener diode. Above the voltage-clamp level, the SAD acts as a variable-resistance, controlling current through whatever impedance is in series with the protected conductor.

Figure 2. Simplified equivalent circuit of the fortress, showing return-stroke current and induced-voltage transients.

For a peak pulse current less than or equal to the maximum specified level (nominally tens of amperes), clamp voltage is held to an essentially constant level. Because it exhibits resistance, higher peak current (i.e., a few hundred amperes) causes the actual SAD voltage to rise to two to three times the specified clamp value. Lead inductance, in conjunction with a high di/dt , can increase this by several more times.¹ Although the SAD is designed to absorb higher energy surges (e.g., 1.5 kW for 1 ms) than an ordinary zener diode, excessive energy (two to four times the rated value) will cause junction heating and can lead to a subsequent short-circuit failure (or an open circuit for energy in excess of 10 times the rated value).

Note that a metal oxide varistor (MOV) is a nonlinear-resistance voltage-clamping device capable of much higher pulse-power dissipation than a SAD. MOVs typically have higher clamp voltages than SADs for the same input currents. They function very well in ac applications because they do not continue to conduct current after the transient has subsided. The prototype LIDS we tested did not use MOVs, but they are being used in actual NTS test events.

The gas tube, a hermetically sealed, gas-filled spark gap, is a high-energy, voltage-controlled switching device that uses the high conductivity of an electric arc as a "crowbar." It is capable of conducting very large currents (tens of kiloamperes) while maintaining a low arc voltage (typically 20 to 30 V) that is essentially independent of arc current. However, before the gas can reach its fully ionized, high-conductivity state, an impulse (sparkover) voltage (typically two to five times the specified dc breakdown value) must exist across the gas tube for a finite time interval (ranging from

nanoseconds to microseconds, depending on the voltage rate of rise, dv/dt). To extinguish the arc, the current must be greatly reduced (typically to less than 200 mA), a fact that must be considered when using gas tubes with ac power circuits.

When the circuit to be protected cannot tolerate the gas tube's high sparkover voltage, a multistage (hybrid) limiter must be used. For our application, the hybrid consists of a shunt-connected gas tube, a series impedance, and a shunt-connected SAD (Fig. 4). Depending on the application, the series impedance may be either a resistor (capable of high pulse cur-

rent—e.g., 20 W) for signal circuits, or a very-low-resistance inductor (e.g., resistance = 0.1 Ω , inductance = 65 μH) for power circuits.

A few nanoseconds after its onset, the induced transient reaches the clamp-voltage level. The SAD begins to shunt a major portion of the rising transient current, which is still fairly small this early in time, from ground to the conductor and, thus, away from the protected component. As explained previously, the voltage across the SAD may exceed the nominal clamp value by a factor of 2 or 3, depending on the current magnitude. The remaining voltage is dropped across the series impedance.

Figure 3. Transient-limiter components.

Figure 4. Hybrid, low-capacitance, bipolar transient limiter.

When the transient reaches the gas-tube sparkover voltage for the requisite time interval, an arc is initiated. The major portion of the transient current now flows through the arc, and the voltage on the conductor falls to a low value (the arc voltage). Note that without the series impedance, the SAD would hold the voltage across the gas tube to below the sparkover value, keeping it from firing. All of the transient current would flow through

the SAD, subjecting it to excessive power dissipation and possibly causing it to fail.

Design Considerations and Trade-Offs

Wherever possible, design of transient limiters must satisfy the system's suppression requirements without interfering with normal operation. Operating voltage, current, and frequency response must be considered along with the

anticipated transient voltage and current waveforms. Selection of a single-stage vs hybrid limiter is governed by a knowledge of the system's susceptibility level. For example, for the same operating voltage level, a hybrid unit generally limits transient voltage to a lower level than does a single-stage unit. However, the hybrid limiter introduces a series impedance that may impact normal system performance.

Selection of the limiting device for a single-stage limiter or the transient-input stage of a hybrid limiter must take into account maximum anticipated transient current, allowable follow current (in ac power circuits), and normal system operating voltage and frequency constraints. High-peak-current gas tubes or MOVs are generally used in the input stage. The series impedance will be determined by current and frequency requirements. Power circuits, generally high current at dc or low frequency, require minimal voltage drop and are best served with a low-resistance inductor. Low-current signal circuits require a resistor, with a high-pulse-current capability, to minimize signal attenuation and waveform distortion over a range of frequencies.

The output stage of a hybrid is selected for its clamping-voltage characteristic, based on susceptibility levels of the circuits to be protected. Usually a SAD or MOV is used, although a device known as a Surgeclor, a voltage-triggered, crowbar device, could also be employed. Because we did not have an opportunity to test a Surgeclor, it will not be discussed.

At a given operating voltage, the SAD has a better clamping-voltage characteristic for low-current transients than the MOV; an MOV can sustain significantly higher currents but exhibits a somewhat higher

Figure 5. (a) Oscillogram of a Marx generator-produced, 145-kHz, damped-sinewave current applied to the test object. (b) Expanded view of (a), showing a 4-MHz oscillation on the leading edge to obtain a high di/dt . The steep leading edge of the wave produced a di/dt in excess of 200 kA/μs.

clamping voltage. The clamp-response times of both devices are comparable for lightning-type transient voltages, exhibiting rise times of less than 100 ns. Although SADs have significantly lower capacitances than MOVs, both devices may degrade the high-frequency performance of a protected system. This problem can be overcome by placing a low-capacitance diode in series with either transient limiting device.

When selecting the output device for a hybrid limiter, one should remember that it must be able to accommodate the rising surge current until the transient reaches the voltage required to bring the input stage into heavy conduction. This is particularly important when using a SAD because its maximum peak current (inversely proportional to its clamping voltage for a given pulse duration) can be quite low for higher-voltage devices. Exceeding the limits of either peak current or pulse duration will cause the SAD to fail in the short-circuit condition. Although transient protection will be provided by the short circuit, a return to normal operation will not be possible until the SAD is replaced. Where such a failure is undesirable and a somewhat higher clamping voltage can be tolerated, an MOV would be a better choice.

Testing

The first tests subjected the fortress to full-threat-level simulated lightning (at 200 kA/ μ s and at 200-kA peak). Initially, a 1.4-MV Marx generator, with an external peaking capacitor, produced a pulse consisting of an underdamped, 145-kHz oscillatory wave with a 4-MHz underdamped wave on its leading edge. The peak current was 48 kA with a rise rate (di/dt) somewhat greater than 200 kA/ μ s (Fig. 5). Test

pulses were applied via a 0.5-m air-spark gap directly to the conductors of a short cable (approximately 0.8 m) whose 360-deg backshell connector was mated to a feedthrough receptacle on the fortress bulkhead. In the next tests, a bank of parallel-connected, high-energy storage capacitors was used to produce a 20-kHz underdamped wave having a peak current of 200 kA and a rise rate of 15 kA/ μ s. These pulses were

applied to the outer shield of the test cable, which was intentionally shorted to the conductors.

Testing was then moved to the Rocket Triggered Lightning Facility at the J. L. F. Kennedy Space Center in Florida. The fortress was placed on a wooden launch platform and connected to the platform's grounding system. A 7-m-long test cable was connected to the fortress and suspended vertically from a wooden

Figure 6. (a) Multiple return strokes for the rocket-triggered lightning program. (b) Expanded scale of the first return stroke in (a).

Figure 7. Examples of surge-testing waveforms. Voltage and current values, per ANSI/IEEE 587, are shown in parentheses.

Figure 8.
(a) High-current, simulated lightning pulse.
(b) Current within the fortress, resulting from the pulse in (a).

support. Approximately 0.5 m from its far end, the cable's outer shield was exposed and connected to a horizontal lightning rod. At the far end of the cable, all conductors were shorted to the shield. When the thunderstorm-produced electric field conditions were acceptable, a 1-m-long rocket (commonly used by French farmers for hail suppression) was launched. It deployed 700 m of Kevlar-jacketed, 0.2-mm-diam wire connected to the launch pad's grounding system. The wire was vaporized by a relatively low-amplitude (nominally 1-kA) continuous current, forming an ionized channel in the air.²

Multiple return strokes then followed, traveling from ground to cloud via the fortress, cable shield, lightning rod, and ionized channel. The fortress was subjected to 22 triggered-lightning flashes containing a total of 80 to 100 return strokes. The maximum peak current was 52 kA, with an overall average of 17 kA. The waveform of the high-current flash is shown in Fig. 6.

From our preliminary observations and subsequent analysis of the data by an independent consultant, we concluded that the fortress design concept is very effective in providing protection against full-threat-level lightning strokes. Transient currents penetrating the barrier and the corresponding transient voltages applied to system components were reduced to safe

levels. In addition, the system components sustained neither damage nor change of characteristics.

However, the analysis did reveal what appeared to be several anomalous transient limiter responses.³ Consequently, we have also tested the limiters using a standard, commercially available surge generator. These tests, at low to medium energy levels, represent a valuable supplement to our more dramatic tests. They have made it possible to carefully examine details of the limiters' performances and to ensure that we do not have any blind spots. We selected the test waveforms (Fig. 7) to represent a reasonable spectrum of waveforms with slow and fast rise times, and short and long durations.

They provided a range of conditions to which the limiters had not been previously subjected. The waves we used were ANSI/IEEE C62.41, category-B, ringwave and unipulse, and $10 \times 1000\text{-}\mu\text{s}$, 1.5-kV open-circuit, 250-A short-circuit waves.

Anomalous Transient Responses

Figure 8a shows the waveform of a high-current simulated-lightning pulse (I_{ex}) applied by means of a short coaxial cable to a single-gas-tube transient limiter. The corresponding internal current (I_{in} , Fig. 8b), determined predominantly by gas-tube conduction, does not follow the applied current. There is an initial time delay before I_{in} begins to flow and a subsequent delay after each I_{ex} zero crossing. When the transient voltage (resulting from I_{ex} flowing through the cable's shield impedance) reaches the gas-tube sparkover value, an arc is established, and I_{in} begins to flow. When

I_{ex} falls to nearly zero, the arc is extinguished, and I_{in} goes to zero.

The transient output voltage of a hybrid limiter (gas tube, resistor, and SAD) subjected to a high-current simulated-lightning pulse (Fig. 9a) is seen in Fig. 9b. Initially, voltage is clamped by the SAD. When the gas tube fires, the voltage falls to the low-arc voltage. After 250 μs , I_{ex} near the zero crossing is low, causing the arc to extinguish. The voltage across the gas tube jumps up, but the output is again held to the SAD level until the gas tube refires. Finally, I_{ex} is too low to produce a

gas-tube voltage high enough to reestablish the arc, and the SAD again provides clamping.

Results of Surge Generator Testing

The earlier discussion of gas tubes pointed out that the sparkover voltage required to establish an arc increases with transient voltage rise rate. This is seen in the oscillograph (Fig. 10) of transient voltages measured across a 230-V (20-kA) gas tube for generator open-circuit voltages of 1 to 5 kV ($1.2 \times 50\text{-}\mu\text{s}$ unipulses).

Figure 9. (a) High-current, simulated lightning pulse. (b) Voltage at the output of the hybrid transient limiter, corresponding to the pulse in (a).

Figure 10. Voltage across a 230-V gas tube for a $1.2 \times 50\text{-}\mu\text{s}$ pulse for four open-circuit voltages.

Figure 11. Arc voltage across a 3-kV gas tube for a $8 \times 20\text{-}\mu\text{s}$ test wave as a function of peak short-circuit current.

In Fig. 11, the arc voltage across a 3-kV gas tube increases as a function of the peak current of the $8 \times 20\text{-}\mu\text{s}$ test wave.

Next, the crossover between the output and input stages of a hybrid limiter is observed for several values of transient voltage. The output voltage responses of a hybrid circuit using a series carbon resistor are shown in Fig. 12. A 400-V (peak open-circuit, $1.2 \times 50\text{-}\mu\text{s}$) test pulse did not fire the 230-V gas tube. Thus, the output voltage was clamped solely by the SAD, which carried the current for the entire pulse duration. For a 1-kV pulse, the SAD clamped the voltage for approximately $2\text{ }\mu\text{s}$, at which time it was reduced to the gas tube's arc voltage. The SAD's clamp voltage was slightly higher because of the increased current it had to conduct. A 6-kV pulse produced the highest rise rate and, consequently, the highest voltage across the gas tube, albeit for a much shorter time. The voltage was clamped by the SAD for the short interval prior to the gas tube's firing. The SAD's clamp voltage and the gas tube's arc voltage were elevated because of the large current associated with the 6-kV pulse.

Figure 13 compares the responses of a SAD with those of an MOV. The devices were used in the output stages of two identical hybrid limiters, which had 230-V gas tubes (input stage) and series inductors. The test wave was a 1-kV, $8 \times 20\text{-}\mu\text{s}$ unipulse. Although the MOV does not exhibit the sharp clamping of the SAD, its response is reasonably close, and it is capable of dissipating much higher energy levels. The

ringing on the MOV waveform is attributed to its higher capacitance in conjunction with the limiter's series inductor.

Conclusions

The use of full-threat-level simulated lightning and rocket-triggered natural lightning demonstrated that the fortress concept provides lightning protection. Because transient limiters play an important part in achieving that protection, it was important to understand their performance characteristics under actual surge conditions. By using properly instrumented surge tests, we obtained information that was not provided by the manufacturers' data sheets. This information will aid in the identification of any blind spots in future designs.

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Figure 12. Output voltage waveforms for a hybrid transient limiter, showing crossover between output and input stages.

Figure 13. Output voltage waveforms for a hybrid transient limiter with different output stages.

Lightning Threat Warning: Anticipating the First Flash

R. T. Hasbrouck

At the Nevada Test Site (NTS), where lightning occurs throughout the year, personnel and equipment can be at risk. Much of the work associated with a nuclear test event is done outside in open areas and involves the use of tall, metal cranes and towers as well as miles of electrical cables running along the ground. A portion of these cables are connected to the nuclear explosive test device system. LLNL's lightning-invulnerable device system concept (LIDS) has been implemented at the NTS to provide protection by conducting lightning current away from the device system via a low-impedance path between ground (Earth) and the lightning channel. (See Ref. 1 for a detailed discussion of the LIDS.) Although the LIDS offers protection for the device system against lightning strikes, personnel safety is best served by providing timely and credible warnings before the first flash.

Lightning, although unpredictable, does announce itself in a variety of ways. A distant thunderstorm does not represent an immediate local threat, and the cloud-to-ground (C-G) lightning it produces provides some advance warning if its audible or electromagnetic (visible or radio-frequency) signals are detected. However, an unanticipated C-G flash can come as an unpleasant and dangerous surprise. Effective lightning-threat warning depends on having the ability to alert designated responsible individuals to a developing threat so they can make the appropriate decisions

regarding work (i.e., to continue, stop, or resume the activity). The alert should come only when a legitimate threat exists, and the end of the threat must be properly recognized so that the endangered activity is neither curtailed for an unnecessarily long period nor resumed while a danger still exists. However, to be able to recognize a developing or diminishing threat, we must understand as much as possible about lightning and how it is produced.

Atmospheric Electrification

The air in our atmosphere is electrically conductive as a result of ionizing radiation. Globally, atmospheric electrification can be represented by the simplified schematic in Fig. 1. Calculations that take into account the surface area of the Earth and the resistance of a column of air between sea level and 100 km (in the ionosphere) show the global resistance of the atmosphere to be about $230\ \Omega$. The resistance of the dynamo region (80–200 km) has been calculated to be $30\ \text{m}\Omega$, and the estimated global resistance of the Earth's surface is about $1\ \text{m}\Omega$.

Measurements made in fair weather, far from thunderstorms, show that the Earth carries a negative charge relative to the ionosphere. The current density is $-2 \times 10^{-12}\ \text{A}/\text{m}^2$ and is accompanied by a downward-directed electric field of about $-100\ \text{V}/\text{m}$ at the Earth's surface. This parameter is the fair-weather electric field, a

vector quantity that is normal to the horizontal, equipotential surface of the conducting Earth. Its algebraic sign is based on convention. Because height is normally considered to be positive in the upward direction, the fair-weather potential gradient (expressed in volts per meter) is positive. In electrostatics, the convention is for an electric field vector to point in the direction of movement of a positive test charge. In this case, the test charge moves downward, opposite to the potential gradient, thus giving the fair-weather electric field a negative sign (i.e., same magnitude but different sign).

Atmospheric potential, the average potential between the ionosphere and the Earth's surface, has been measured to be approximately 270 kV (ranging from 180 to 350 kV). The sum of all currents flowing in the Earth's fair-weather regions is about $-1\ \text{kA}$. The total charge in the global atmosphere is calculated to be about $677 \times 10^3\ \text{C}$, with a corresponding capacitance of 2.9 F.

The final element in this global atmospheric electrical circuit is the generator. At any time, approximately 2000 thunderstorms are in progress around the planet. Lightning from these thunderstorms is one way of lowering charge to the Earth. Others are conduction current, convection, and precipitation. With a global atmospheric current of $-1\ \text{kA}$ and 2000 storms in progress simultaneously, each storm should contribute an average of about 0.5 A to the ionosphere. The circuit is completed through the $230\text{-}\Omega$ global resistance of the

planet's fair-weather regions. Within the cloud, the conductive air is responsible for a discharge current of 0.2 A, and the resulting source current of the generator is 0.7 A. Additional calculations show a typical thunderstorm as having source potential of 200 MV, a capacitance of 1 μF , and electric energy equal to 140 MW·h (for a 1-h storm).

Thunderstorms, the major source of electromagnetic energy in the lower atmosphere, are considered to be the driver of the global circuit. They, in turn, are the result of atmospheric temperature gradients produced by solar heating. Therefore, severe thunderstorms occur most frequently in the midafternoon in the temperate regions during

spring and summer and in the tropical regions during the northern hemisphere's winter.

Thunderstorms fall into two categories: convective and frontal. Convective storms are local in nature. They usually occur in the mid- to late afternoon, have relatively short life cycles of 1 to 2 h, and produce moderate to heavy amounts

Figure 1. The global atmospheric electric circuit. The thunderstorms act as generators, with the rest of the world completing a resistance-capacitance circuit.

of lightning, rain, wind, and sometimes small hail. Frontal storms are self-propagating and produce severe lightning, large-diameter hail, high winds, and sometimes tornadoes.

Convective storms develop in the atmospheric region known as the troposphere, which extends from the surface up to about 15 km. In this region, temperature decreases as the altitude increases. Convective storms require a layer of moist air extending to an altitude of about 1 km, strong solar heating of the ground and adjacent air, and an unstable atmosphere (an ambient temperature that falls rapidly with increasing altitude). Small parcels of moist, heated air will rise as long as their temperatures are higher than that of the air through which they pass. Since increasing altitude is accompanied not only by decreasing temperature but also by decreasing

atmospheric pressure, the rising air parcels expand, which results in cooling and condensation of the water vapor they contain. The latent heat of condensation released into the parcels causes them to remain at higher than ambient temperatures and allows them to continue rising.

The action of rising air parcels leads to the formation of individual cumulus clouds, which is the first stage of the local thundercloud and lasts for 10 to 15 min. Gradually, the individual cumulus clouds merge to form a much larger cumulus congestus cloud. This cloud, in which all of the air motion is upward, may reach 1.5 km in diameter and exhibit a well-defined top, which rises at a rate of 10 to 30 m/s.

As this cloud continues to grow, small cloud drops and large water drops form. The large drops, now too heavy to be supported by the

convective updraft, begin to fall as rain. As the lighter cloud drops continue their rise, ice particles form in the -10 to -20°C region, releasing additional latent heat in the process. Within the growing cloud, several types of precipitation can now occur: rain or snow in the warmer regions and ice crystals and hail in the colder regions.

Condensation in the upper part of the updraft and an increase in air density resulting from rain in the cloud's middle region cause the cloud to lose its buoyancy. The thundercloud, or cell (Fig. 2), has now reached the mature stage and is referred to as cumulonimbus (CB in meteorological terms). It has a characteristic flattened, anvil-shaped top, which may rise beyond 15 km into the stratosphere (where temperature remains constant or increases with altitude). During the 15 to 30 min that the CB usually lasts, heavy precipitation takes place, accompanied by appreciable lightning and a strong, cold, evaporating downdraft.

The storm moves into its final, dissipating phase when the cold downdraft counteracts the warm, moist updraft that has been supplying the cell. Precipitation diminishes, and the severe updrafts and downdrafts fall off, as does lightning activity. After about 30 min, the remainder of the water vapor has evaporated and the cloud has blown away.

Frontal thunderstorms generally form near the boundary of a moving cold front and a region of warm, moist, stationary air. Lacking buoyancy, the cold front moves in under the warm air, pushing it up and generating a cell as described above. The cycle of updraft followed by downdraft is repeated as the front moves along.

Figure 2. Typical, mature cumulonimbus thunderhead. Arrows inside the cloud depict strong updrafts.

Although not all thunderstorms develop in the same way, these are the two most common types. The details of thunderstorm formation continue to be studied.

Lightning

When we see lightning or hear thunder, we are observing the manifestations of a dramatic and sudden charge transfer on the order of 10 C (median value). This transfer, the charge carried by 10^{20} electrons, occurs in a few hundred milliseconds. For the transfer to take place, the cloud must be polarized (i.e., separate regions of positive and negative charge must exist). In a simple cloud model, these two vertically separated regions form a dipole, with the negative (N) region located nearest the Earth. (For an in-depth discussion of cloud electrification, see Ref. 2.)

When charge separation within a cloud causes local electric fields to exceed the dielectric strength of the air, the air breaks down, and a lightning discharge takes place. If cloud altitude and the presence of water and ice particles are considered, a typical value for the breakdown electric field is approximately 1 to 2 MV/m.

Intracloud Lightning

Intracloud lightning (I-C) is the most frequent form of lightning, although the opacity of clouds limits visual support of this fact. Intercloud lightning (i.e., between separate clouds) occurs relatively infrequently.

Charge redistributions within the cloud (I-C lightning) initiate the storm-cell discharge process. For each discharge, a double-ended, tree-like streamer (or leader) carries positive charge from the positively charged region to the negatively charged region along paths

that possess the greatest concentration of charge. Each time a positively charged streamer reaches a small concentration of negative charge, a recoil streamer (K-stroke, nominally 1-kA peak current) returns along the ionized channel, neutralizing its positive charge. When a connection is made between highly charged regions, a high-current return stroke (e.g., 10-kA peak) takes place. Within a few hundred milliseconds, a lightning event transforms electrostatic potential energy into electromagnetic energy (radio and light waves), heat, and acoustic energy (thunder).

In 1988, Williams reported³ that maximum I-C activity and a polarity reversal of the electric field at the ground were found to be concurrent with the period of peak updraft. This takes place 5 to 10 min before the onset of intense precipitation and the strong downdrafts associated with the collapse of the updraft. Recent studies by the French have shown the onset of I-C lightning to precede C-G lightning by 10 to 30 min and peak total lightning activity to precede heavy precipitation by 5 min. These findings suggest that nature may provide a warning before the onset of intense downdrafts and heavy precipitation.

Because the base of the N-region usually coincides with the freezing-level altitude, a warmer ambient air temperature results in a higher cloud base. Since C-G lightning takes place predominantly between the N-region and the Earth, it is less likely to occur as the cloud-base altitude increases. Global statistics show the average ratio of I-C to C-G lightning is about 10:1 for the equator, 5:1 for the cooler middle latitudes (e.g., the U.S.), and 1:1 for the cold far north. Because of this temperature dependence, a larger percentage of C-G lightning can also be expected from cold storms.

Cloud-to-Ground Lightning

Because of its visibility, much more is known about C-G lightning than I-C lightning. It most frequently lowers negative charge (electrons) to the Earth, making it part of the global circuit. With C-G lightning, the negatively charged end of the previously mentioned double-ended tree emerges from the cloud's N-region. A faintly luminous ionized channel moves toward the Earth in a series of steps, nominally 50 m each, having a duration of 1 μ s/step with a pause of 50 μ s between steps. This channel, called the stepped leader, carries essentially the full potential of the N-region (e.g., -20 to -100 MV). The steps probably result from breakdowns between the high-voltage tip of the leader and small pockets of positive charge in the air. As the stepped leader approaches the Earth, at about 0.2 m/ μ s, its strong electric field causes positively charged streamers to move upward from pointed, grounded objects. When the electric field between the stepped leader and one or more streamers is greater than the dielectric strength of the intervening air, the air breaks down (see Fig. 3). Typically, this striking distance is in the range of 30 to 100 m (a function of the peak return-stroke current). During the leader process, the steps exhibit 1-kA peaks with an average current of -100 A. A negative charge from 5 to 10 C (predominantly electrons), distributed along the channel, is lowered in tens of milliseconds.

With the leader-to-surface circuit now closed by this lowering of the channel's negative charge to Earth, a positive, high-current return stroke proceeds to neutralize the channel as it rushes up to the cloud at a speed of 35 to 100 m/ μ s. The return-stroke peak current produces a sudden

temperature rise (e.g., 30,000 K), making the return-stroke channel highly visible and causing the thunder-producing overpressure. The cloud's charge center, from which the stepped leader originated, is temporarily neutralized. On the average, three to four return strokes occur, separated by tens of milliseconds (or tenths of a second if continuing current is present). The entire event, approximately 500 ms in duration, is referred to as a lightning flash. As many as 26 return strokes have been

recorded for a single flash.

Because of the speeds involved, the human eye cannot differentiate the various portions of the lightning flash. Thus, what we perceive as flickering is actually the result of multiple return strokes.

Positive C-G strokes, in which positive charge is lowered from the positive (P) region, occur much less frequently (10% of all C-Gs, worldwide) than negative strokes (the other 90%). Positive lightning can be observed near the end of a thunderstorm, or in conjunction with

cold storms (in which positive C-G predominates) or severe storms that produce large hail or tornadoes or both.

With I-C lightning, current levels are small and path lengths are short during the initial breakdown within a cloud, generating radio noise predominantly in the VHF spectrum. When a high-current discharge takes place, a peak current of 10 kA can flow through a channel of 1 km or more, producing a strong lightning electromagnetic pulse (LEMP) with a spectral density centered at about 4.5 kHz. As with I-C lightning, the radio noise generated by the C-G return stroke is a low-frequency phenomenon whose spectral density is also centered at 4.5 kHz, diminishing to near zero beyond 100 kHz.

Lightning Threat Warning

As discussed earlier, the global circuit produces a surface fair-weather field of approximately -100 V/m ($+100 \text{ V/m}$ if referring to potential gradient rather than electric field). When charged clouds move into an area or develop overhead, the much higher potential of their charge centers and their proximity to the Earth cause the local electric field to depart significantly from the fair-weather value. As the magnitude of the electric field increases, there is generally a point in time when the polarity reverses. Whenever a lightning discharge occurs, the associated cloud charge center is neutralized instantaneously, followed by a gradual recharging (30 s to 1 min, typically). The surface electric field generally follows these transitions.

Several types of instruments, located at or near ground level, are commonly used to monitor atmospheric electrification. The magnitude and polarity of the dc electric

Figure 3. Development of a C-G lightning flash. The stepped leader advances toward the ground until the striking distance (30–100 m) is reached. The return stroke flashes back along the ionized channel left by the stepped leader.

field at the Earth's surface can be measured with an instrument known as an electric field mill (EFM). The EFM uses a fixed electrode (stator), consisting of several segments, connected to ground via a sensitive current-measuring circuit. The stator is alternately exposed to and shielded from the atmospheric electric field by a segmented, rotating, grounded conductive plate (rotor). During exposure intervals, a charge is induced in the stator by the electric field. During shielding intervals, the charge drains off to the Earth via the current-measuring circuit. This process generates an alternating voltage proportional to the electric field. When the measured field departs significantly from the fair-weather value (e.g., doubles in magnitude or reverses in polarity), dangerous clouds are relatively close (e.g., 6 to 8 km away).

Electric field mills do have several shortcomings. Ideally, the stator should be located exactly at ground level. However, this places the rotor in a position where it can be damaged by, and do damage to, wildlife and people. It can also be buried by dirt or snow or submerged by heavy rain. Raising it above ground level solves one problem but introduces another. A charged body located above a large, flat, conductive ground plane produces electric field lines normal to the plane as well as uniformly spaced equipotential planes that lie parallel to the ground plane. A local discontinuity such as a grounded upward protrusion will essentially compress the equipotential planes, thus enhancing the field strength around the protrusion and thereby increasing the apparent magnitude of the measured electric field. Positioning the EFM above the Earth's surface

produces such an enhancement. This apparent increase in sensitivity can be compensated for by reducing the sensitivity of the signal-conditioning amplifier. In addition, EFMs should be installed away from tall, grounded structures such as buildings, towers, light poles, and security fences. The recommended practice is to separate an EFM from a structure by a distance equal to at least twice the structure's height.

The phenomenon of space charge presents a much more serious problem. When the magnitude of the surface electric field exceeds about 2 kV/m, grounded, elevated, pointed objects on the surface (trees, bushes, man-made structures) go into corona-point discharge, producing a layer of monopolar ions (space charge) with a polarity opposite to that of the cloud charge causing the corona (i.e., generally positive). This space charge, an unpredictable variable concentrated within several tens of meters above the Earth, affects electric fields near the surface, masking a surface-mounted EFM from the true magnitude of the cloud's electric field. Space charge also makes it impossible to accurately correct the enhancement effect associated with an elevated EFM. Even if an EFM's immediate environment is free from corona-producing pointed objects, surface winds can blow space charge in from nearby areas. The relatively low mobility of the ions allows the space charge to persist for 5 min or longer after the cloud-produced field that caused it has changed in magnitude or polarity.

Finally, the motor-driven rotor is subject to damage and requires periodic maintenance. Particulate buildup on either the rotor or stator will affect the calibration.

Detection of Electrical-Discharge Activity

If a suspicious storm cloud is off in the distance, we cannot determine whether the cloud is electrically active, i.e., whether it represents a possible threat, unless an electrical discharge is detected. How much warning time do we have before the first C-G flash occurs? From statistical data, we know that cloud icing and electrification commence within 5 to 10 min after onset of the strong updraft and coincident with the first weather-radar echoes from aloft; the first discharge, almost always I-C, takes place in another 5 to 10 min; and the first C-G flash occurs 15 to 20 min after the initial radar echo. Thus, the warning time for the distant storm depends on how far away it is and what types of observations are being made. Even if we know the distance to a storm cell and its velocity (mean wind velocity), we still cannot predict when and where lightning will strike because C-G lightning exhibits a random-walk pattern with an average step of approximately 3 km from flash to flash.

If a convective storm develops overhead and radar data are available, the warning time may be 15 min, although this type of storm has been known to go from a clear sky to the first flash in 10 to 12 min. If the initial I-C discharge is the first one observed, a C-G flash can be expected in 10 min or less, even immediately sometimes. Although 1 h is the typical duration of a convective storm, rapidly developed storms tend to dissipate quickly, and a slowly developed storm dissipates slowly.

Either visual or electro-optic observations can be used to detect both I-C and C-G discharges. Unless the light pulse is obscured or diffused by dark clouds, a single observer should be able to provide such information as bearing to the pulse, approximate range (by timing the flash-to-thunder interval), and time of occurrence. The high peak temperature of the return-stroke channel causes an audible pressure pulse (thunder) of about 10 to 30 atm with a peak spectral amplitude at 100 Hz. Thunder can be heard approximately 25 km from an I-C discharge and 5 km from a C-G flash, depending on such factors as the intensity of the discharge, wind direction, and terrain. Both the light pulse and thunder are positive indicators of an active electrical storm.

In addition to light pulses, cloud discharges produce electromagnetic radiation known as atmospherics or spherics over a fairly wide range of frequencies. The short path lengths associated with initial breakdowns and stepped leaders result in radiation that is predominantly in the VHF portion of the radio-frequency spectrum. With a suitable receiver, we can detect these precursors to C-G lightning activity. The radiation from a typical C-G return stroke is equivalent to that of a 20-MW spark-gap transmitter, with a signal that predominates well below 1 MHz. Because the electrostatic field intensity component of this radiation varies inversely as the cube of the distance (the $1/D^3$ rule, where D is the distance from flash to receiver), the strength of the received signal provides some indication of the distance to the flash.

A simple AM-radio receiver tuned to the low end of the broadcast band (0.5 MHz) can be used as a

rudimentary C-G flash detector. If weak, periodic, static impulses are heard, a storm cell has started producing C-G lightning. Increasing amplitude indicates either that the storm is approaching (a frontal storm) or that larger-amplitude strokes are taking place. An increase in the number of static "crashes" per minute (the flash rate) means the storm is growing in intensity. When a frontal storm reaches peak activity, the lightning-produced signals will occur at essentially regular intervals.

A somewhat more sophisticated flash-warning instrument consists of a filter tuned to the low-frequency portion of the lightning stroke's spectrum and an amplifier. Because the received signal strength of an average-amplitude (20-kA) C-G flash can be estimated by the $1/D^3$ rule, the gain of the amplifier can be set to provide a specific output signal corresponding to a particular distance. Unfortunately, lightning is far from being a constant source—studies have shown that strokes occurring at a given fixed distance produce field intensities that can vary by as much as a factor of 100. Thus, we cannot accurately determine the distance to a single stroke. However, statistics come to the rescue. By using several amplifiers with gains corresponding to different flash distances (i.e., highest gain for farthest and lowest gain for closest), we can quantize the signals. The mean storm distance corresponds to the range showing the highest number of strokes.

A recently developed electro-optic sensor can detect lightning pulses not visible to the eye, e.g., distant I-C lightning under daylight conditions. Because I-C lightning generally precedes C-G lightning by 10 to 15 min, this sensor can be used for pre-first-flash warning. When

this small, lightweight, hand-held instrument is pointed at a suspicious cloud, its first audible beep (an electrical output pulse is also produced) warns the operator that the cloud is beginning to produce discharges. These sensors also can be used in an unattended, surveillance mode by mounting them and connecting their electrical outputs to a suitable alarm system. The acceptance angle of the detector's lens is selected to provide the desired coverage.

Location and Tracking of Cloud-to-Ground Lightning

In the simplest form of lightning locating, a lone observer determines the bearing of a single visible C-G flash, counts the number of seconds between the lightning and the thunderclap, and divides by three to obtain the approximate distance in kilometers (or by 5 to obtain miles—velocity of sound is approximately 1 km/3 s or 1 mi/5 s). If the flash-bang interval is 3 s or less, the storm is essentially overhead. This flash-bang technique has been made more suitable for scientific research by combining a light-sensitive detector, a microphone, and an intervalometer. By using several widely separated observers or sensors, we can obtain several bearings and locate the strike point by triangulation. However, this technique has some obvious shortcomings.

In two significantly more sophisticated methods (time of arrival and magnetic direction finding), receivers at several widely spaced locations detect the strong electromagnetic signals radiated by C-G lightning. The resulting data are transmitted to a central computer for processing and distribution to remote display terminals. These systems allow a large number of flashes over a wide area to be

located and tracked. Because such data can be archived, subsequent analysis can provide valuable statistical information such as thunderstorm frequency, history, and preferential paths.

Lightning Threat Warning at the Nevada Test Site

Designated responsible individuals who combine all available information with experience and common sense are necessary to ensure that the NTS personnel who may be affected by lightning receive timely and credible threat warnings. Several different methods are available, both at the NTS and the Atlas Facility in North Las Vegas, for providing the necessary information to these individuals. The most extensive installation, at Area 27, is depicted in Fig. 4. Following are brief descriptions of the instrumentation being used.

MRI Sensor. Although no longer manufactured, the Meteorological Research, Inc. (MRI) sensor is still in use at the NTS, both at Area 27 and

at various test-event ground-zero sites. This early-1970s, portable instrument uses a low-level radioactive source for measuring potential gradient (PG) and a spherics receiver for providing estimated distances to C-G flashes. Its output signals are recorded and displayed by means of a strip-chart recorder. An ancillary chaser, designed by LLNL-Nevada, provides an audible warning when the PG exceeds the alarm limits (e.g., 1 kV/m and 2 kV/m). Because it is located on the surface within Area 27's Baker compound (a security area), this instrument is affected both by wind and the space-charge layer (as previously discussed). Since the compound is surrounded by high security fences (many sharp points) and tall light poles, it is reasonable to expect that a significant space-charge layer will be produced when thunderstorm clouds are near or above the area. Recall that corona discharge takes place when the PG at the grounded object exceeds 2 kV/m. Because of field enhancement, the

top of a 5-m-high barbed-wire fence will start contributing to the space-charge layer when the PG measured at the surface is approximately 600 to 700 V/m.

Atmospheric Potential Monitor.

The recently developed atmospheric potential monitor (APM) is a commercial instrument that permits detection of potentially hazardous electric fields while minimizing or eliminating problems associated with space-charge layer, field enhancement, wind effects, and moving parts. Following the 1989 lightning season, an APM was installed at the NTS/Area 27 on a small hill outside and above the Baker compound. (A second APM was installed on top of the Atlas Facility's 110-ft-tall tower building.) The APM uses a sharply pointed metallic probe placed well above the ground (20 m at Area 27) and energized by a 3-kV, low-current, ac power supply. The combination of height and high voltage causes the probe to be in continuous corona discharge, even under the weak PG

Figure 4. Current lightning threat warning system in place at the NTS. ALDS = automatic lightning detection system, DAS = data-acquisition system, dE/dt = time rate of change of the electric field, EFM = electric field mill, MRI = MRI sensor, PC = personal computer, and PG = potential gradient.

(nominally 100 V/m at the surface) associated with clear weather. The APM's electronics measure the magnitude and polarity of the discharge current and send an output signal, proportional to PG, to a remotely located computer. The computer is used to acquire and display data from the APM and to provide audible and visual warnings when the PG exceeds the alarm limits (see above). Data from an EFM and an anemometer are also sent to the computer. Because wind-blown charged particles can cause PG sensors to provide spurious responses, it is important to monitor wind velocity and direction. Data files can also be examined in Livermore by means of modems and a dial-up phone line.

Electric Field Mills. Along with the MRI sensor, two EFM's are located within the Area 27 compound. Output from either EFM can be recorded by the computer, allowing us to compare it with the APM. As with the MRI, space charge will adversely affect the EFM's readings.

Optical Lightning Detector. Two hand-held, optical detectors are available for use by the aforementioned responsible individuals. As discussed, these instruments can provide early warning by detecting electrical discharges within a storm cloud well in advance of the first C-G lightning flash.

Automatic Lightning Detection System. The automatic lightning detection system (ALDS) is operated for the NTS by the Weather Service Nuclear Support Office (WSNSO). It is a large-scale commercial system that uses the magnetic-direction finding technique to locate and track C-G lightning flashes. Color video displays indicating thunderstorm location, intensity, and direction are

provided to WSNSO forecasting personnel and to various interested parties at the NTS. Because this system only detects C-G lightning, it cannot provide a threat warning for convective storms that are typical during the late spring and summer at the NTS. However, some degree of warning is provided in the case of frontal storms that typically move into the NTS area during the fall, winter, and early spring.

Flash Warning Sensor.

The flash warning sensor (FWS), a simple, stand-alone instrument, receives the extremely low-frequency signals produced by C-G flashes and quantizes them into four, separate, signal-strength levels corresponding to four distance ranges. Digital counters record and display the number of flashes at each range. Although the wide peak-amplitude variations of C-G flashes result in significant uncertainty, the FWS does warn of the existence of an electrically active storm. When properly calibrated, it can provide an estimate of range once a reasonable number of flashes (e.g., >20 for a particular range) have been registered. An audible alarm signal is produced when flashes are detected at a specified range. As with any technique requiring the occurrence of C-G flashes, the FWS has limited usefulness as a threat warning sensor. At Area 27, the FWS output is fed to the computer for display.

Future Plans

Because the APM is a new technique, our initial objective is to gather and analyze data from the Area 27 system and compare it with other data (i.e., ALDS, MRI, EFM, and FWS) as well as with actually observed weather conditions.

Although this instrument has been extensively tested at the Kennedy Space Center in Florida, it has not yet been through a lightning season in a high-desert region such as the NTS. We will also share information with personnel from Sandia National Laboratories who are operating a two-sensor APM system at the Tonopah Test Range. One anticipated problem is how to differentiate between high-PG alarms resulting from blowing sand and dust and those caused by an electrically hazardous storm cloud. Of particular interest will be the use of APM data to evaluate the extent to which space charge affects the MRI and EFM. We also need to determine the most effective method for presenting lightning threat warning information to the designated responsible individual. Finally, a desirable long-term goal would be to develop an artificial-intelligence/expert-based system that could produce timely and credible lightning threat warnings with a minimum of human intervention. Such a system not only would be useful for the NTS but also would have excellent technology transfer potential.

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Nuclear Chemistry

3

The main mission of the Nuclear Chemistry Division is to provide experimental data to understand the performance of nuclear explosives in underground tests. We rely on radiochemical diagnostics to determine the basic performance criteria of these tests—total fission and thermonuclear yields. The increasing complexity of the tests and the desire for more detailed data require an ongoing research and development (R&D) program to improve and expand our arsenal of diagnostic techniques.

To understand the physics of a nuclear explosive experiment in detail, we must determine yields of individual parts, burn asymmetries in fissile and thermonuclear fuels, fast-neutron outputs, and the extent of shell instabilities. Firm data on these performance details are needed to verify computational-model predictions or to identify deficiencies in the models, thereby leading to a better understanding of the

physics of nuclear explosives. In this section, we report R&D in support of the Division's radiochemical diagnostics mission.

In studying the performance of a nuclear explosive, we begin by loading various materials into the device. Some materials, called tracers, measure the amount of device recovered in postshot sampling. Materials used to measure basic device performance are called detectors. The basic constituents of the device itself may be used as tracers or detectors.

Typically, actinides not common in nature are used as tracers. Their different chemical and physical behavior during and after the nuclear explosion can contribute to misinterpretation of device performance unless special precautions are taken. We discuss these precautions in this chapter. We also describe the development of a chemical separation technique for bismuth, a material we are developing as a new detector.

More and more materials are required as tracers or detectors as we seek to find ways of recovering more useful information from a single test. After detonation, samples are obtained by drilling back to the post-shot cavity produced by the nuclear explosion. Solid samples, or cores, are assayed at the drill site by a new, mobile, gamma-ray spectrometer system. This system allows us to select high-quality samples within minutes of recovering the sample, thus providing better samples for further analysis in the laboratory. Gas samples are also obtained post-shot, and we are developing a technique to recover high-quality gas samples through the same drillstring that is used for core samples. This technique not only reduces field costs but also has a better chance of returning good samples for short-lived, gaseous radionuclides. In this section, we discuss improvements to the solid-core field gamma-ray spectrometer and our experience with drillstring gas sampling.

Field samples are returned to the laboratory for further analysis and interpretation. Solid samples must be dissolved to provide aqueous solutions for radiochemical separations. In the past, this critical step involved a great deal of tedious hand work that subjected the chemists to small hand doses of radiation. To reduce this exposure as much as possible and to provide greater control over the chemical processing of the highly radioactive samples, we completed and tested a new, state-of-the-art, automatic

dissolving facility consisting of 12 glove boxes and a master-crusher glove box. The facility is now used routinely for test samples.

After radiochemical separations have been performed, samples are prepared for nuclear counting or mass spectrometry. This analysis provides a picture of the inventory of nuclear isotopes that are present after the nuclear explosion. Some isotopes are produced by nuclear reactions with materials present in the device, while others represent materials that have been unaltered in the explosion. Interpretation of this large body of interconnected data allows us to develop a picture of the performance of the device.

This interpretation is extremely complex, however, and depends on the physical properties of the nuclides involved, such as certain nuclear reaction cross sections and the yield of nuclides produced by the fission process. Developing new detectors such as iridium and bismuth requires that the nuclear properties be understood in detail. For example, in the extreme conditions of a nuclear explosion, the reaction cross sections cannot be measured. However, by relying on basic nuclear reaction theory and the structure of the nuclei involved, we have developed complex computer models that can calculate the cross sections so the data can be interpreted reliably. We describe some of the efforts to develop successful cross-section models and the basic physics behind them. We also discuss ways in which we are improving the reliability

of our fission yield measurements based on fundamental parameters of the fission process.

In recent years, we have pioneered in the development of detectors that can shed light on the problem of instabilities in nuclear device dynamics. Some of these detectors provide information by sampling the charged-particle fluence in the explosion. Again, the data cannot be interpreted in terms of device performance unless the appropriate charged-particle cross sections are known. However, these cross sections can be obtained by a laboratory measurement. Much effort has gone into developing a reliable, high-accuracy facility for measuring charged-particle-induced cross sections. The facility, some of the measurements, and model calculations of the cross section are described in several reports in this section. These laboratory data are used directly in our postshot interpretations, and they serve as a stringent test of our ability to model nuclear cross sections. We also discuss the use of ruthenium as a charged-particle detector for nuclear tests.

Many techniques that we have developed to diagnose underground nuclear explosions can be used to understand other underground phenomena. The composition and origin of the cavity gas produced in Defense Nuclear Agency nuclear effects tests are important parameters for understanding and predicting the containment of these tunnel tests. We describe an experiment performed on the Misty Echo Event.

Nuclear Test-Experimental Science

Upgrade of a Field Gamma-Ray Spectrometer for Onsite Core Analyses at the Nevada Test Site

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In the 1988 *Nuclear Test-Experimental Science Annual Report*,¹ we discussed the development and implementation of a field gamma-ray spectrometer for performing onsite analyses of drillback cores containing debris from underground nuclear tests at the Nevada Test Site (NTS).

The field gamma-ray spectrometer functions as follows:

- A portable germanium detector is installed in a trailer that during drillbacks is located next to the drill rig.
- Soon after a core has been extracted (as early as 3 d after a test), it is placed in a shielded counting chamber in the trailer. Here, a load cell determines its weight (typically, 50 to 300 g).
- An operator in a second control trailer located outside the potentially contaminated drillback area remotely positions the detector 0.9 to 3.0 m from the core to accommodate different levels of core activity. Good cores contain fission products from 10^{15} to 10^{16} total fissions.
- Readouts of the core weight and sample-to-detector distance are available in the control trailer, where the data are collected and analyzed. Each spectrum is analyzed to establish both the total fission content of the core and the ratio of ^{95}Zr to ^{140}Ba atoms. The analysis uses a code that contains information regarding detector calibration and fission-product yields.

By using this field spectrometer routinely during the past year, we

have been able to determine the weight, fission-product content, and chemical fractionation of a core within minutes after its retrieval. Quantitative measurements of the quality of freshly obtained cores have allowed us to decide which downhole locations should receive the greatest sampling effort and which cores need "high-grading" (selection of the best pieces of the sample) before further analysis.

As we used the system, however, possible improvements became evident. For example, the data were being collected and analyzed with a portable but bulky multichannel analyzer (MCA) that could be used either as a computer or as an analyzer but not as both simultaneously. The procedure was to switch back and forth between using the system first as an analyzer for collecting data and then as a computer for analyzing data. The floppy disks used by the system for storing program and system software had several disadvantages: the switching and data-storage processes were relatively slow (~1 min and ~1.5 min, respectively), and the system was susceptible to failure because of the dusty and dirty environment (several program and data disks became unreadable for just this reason).

Thus, when it became evident that a backup system was necessary, we decided to use the opportunity to upgrade both the hardware and software of the current system.

Computer and MCA Upgrade

The upgrade uses an IBM-compatible computer with an 80386 processor, an 80387 coprocessor, and a removable, 40-Mbyte, Winchester hard-disk drive. All these components are placed in a rack-mountable, rugged, industrial chassis. The computer chassis has a 13-slot, passive backplane that provides space for additional IBM-PC or PC/AT expansion cards. We have added an analog-to-digital conversion card to digitize the analog readouts of the sample's weight and its distance from the germanium detector. The system has a 5-1/4-in., 1.2-Mbyte, high-capacity, floppy-disk drive that can write data on floppy disks (after the data have been sanitized for security reasons). These disks can then be sent to Livermore for archiving. The Winchester drive was chosen for two reasons: to give us faster response times than was possible with the old system (data transfer from computer memory to disk now takes only a few seconds); and, because the information is considered classified, to provide a removable disk that can be secured when it is unattended.

The MCA function in the old system has been replaced with a new system that consists of both hardware and software components installed in the computer. An acquisition interface board with an on-board analog-to-digital converter (ADC) is installed in one of the

computer's input/output slots. The software provides the main display and control functions for the system. The new MCA can acquire data while the computer is being used for other purposes (not possible with the old system).

Figure 1 shows the upgraded system in the control trailer.

Software Upgrade

With the new computer, it was necessary to transfer the software for the spectral-data analysis from DEC Fortran to MicroSoft Fortran for the PC. At the same time, we chose to improve the software, specifically, the user's interface and the data-analysis capability. For each sample assay, we must have sample identification information, sample weight, and the sample's

distance from the germanium detector. With the old software, this was done by polling the user with a series of questions and responses. The new software uses screen menus and forms, as shown in Fig. 2. This approach shows the user all of the information at one time and allows an individual item to be changed without the user's having to step through a series of questions. Therefore, the user can generate events that the software captures, interprets, and responds to; and, rather than being trapped in a fixed sequence of events, the user can move freely from one procedure to another.

In addition, the sample's weight and its distance from the detector are now read directly by the computer from the appropriate measuring

devices through an analog-to-digital interface in the computer. This information is displayed on the screen for verification and can be changed by the user.

From experience with the old system, we had learned that we could, very early in a count, determine semi-quantitatively the quality of a core from the displayed count rates of selected gamma-ray peaks. With the new PC-based MCA, the computer has direct access to the spectral data during data acquisition. The specific data regions used in the data analysis can be read directly from the memory on the data-acquisition board. By using this capability, we can calculate and display, with their statistical precisions, the core sample's total fissions and the ratio of ^{95}Zr to ^{140}Ba atoms. Because these values are displayed continuously from the beginning of data acquisition, we can, within a minute or so of core extraction, decide whether to continue sampling at the current depth or to proceed to a new location.

Finally, we have added a summary report of the core assays to the system. For each hole or sidetrack hole, a file is created into which the assay results of cores from each hole are written. The files are in ASCII format, and a tabulation of the results for any hole may be obtained by simply printing the file.

Field Experience

For initial checkout and testing, we fielded the new PC-based measurement system at the NTS in the Palisades Event, where it was operated in parallel with the old system. Except for a few minor programming problems, the overall performance of the new system was excellent, including significant

Figure 1. The upgraded field gamma-ray spectrometer.

improvements in speed and ease of use. The menu-selection screens and data-entry forms made operation and setup of the new system more convenient and reliable. Its ability to display the core sample's total fissions and the ratio of ^{95}Zr to ^{140}Ba atoms during data acquisition sped up the core-analysis process, thus preventing any slowdown of the drillback operation. The creation of a summary file for each hole aided in the selection of cores for high-grading.

Conclusion

The reliability, speed, and ease of use of the gamma-ray spectrometer system at the NTS have been improved significantly by upgrading the old measurement system to a new PC-based system. The upgrade has greatly improved our ability to effectively sample underground nuclear test debris, and its reliability is essential to the efficiency of the drillback operation. Also, because we now obtain quantitative and continuous real-time measurements of

the quality of each freshly extracted core, we can quickly decide which downhole locations should receive the greatest sampling effort and which cores should receive further attention. Finally, the computing power of this new system gives us the freedom to either expand the data-analysis program or replace it with more sophisticated programs.

Reference

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Figure 2. An example of the interactive screen display provided by upgraded software.

New Core-Dissolving Facility

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Following the underground detonation of a nuclear device at the Nevada Test Site (NTS), solid-core debris samples are returned to LLNL for radiochemical analysis to determine device performance. However, before the core samples can be radiochemically separated, they must be completely dissolved to yield homogeneous solutions. The procedure involves several steps:

- Because the core samples are primarily silicate-containing minerals in which the device debris is included, the dissolution procedure requires that we treat the highly radioactive samples with concentrated hydrofluoric acid (HF) at elevated temperatures.
- Because residual fluoride ions form insoluble compounds with a number of the elements we wish to measure, the procedure also

includes fuming the sample with perchloric acid to eliminate any remaining hydrofluoric acid. Care must be taken to oxidize any organic matter prior to the perchloric acid treatment, because this acid is potentially explosive when it contacts organic material at the temperature required for fuming.

- Because of the high radiation levels and the harsh chemical treatments involved, the dissolution

process must be carried out in a glove-box enclosure under closely controlled conditions.

For more than 20 y, we have processed core samples in the dissolver facility located in LLNL's Building 151. For a given event, typically 9 to 12 samples of silicate-containing minerals (10 to 30 g/sample, including water and drilling mud) are processed in this facility. The beta-gamma radiation level associated with each sample is usually several hundred milliroentgens, but, depending on the diagnostic quality of the sample, it can reach several roentgens.

Because of the increasing difficulty of maintaining our aging equipment and our desire to further reduce radiation exposure to personnel working in the facility, we have recently designed and constructed a new core-dissolving facility that:

- Provides better radiation shielding and reduced sample handling.
- Provides improved control over sample processing.
- Further ensures the quality of our radiochemical diagnostics by providing easy equipment decontamination between tests.

The Core-Dissolving Facility

The new facility (Fig. 1) consists of a master crusher box and 12 glove boxes, all interconnected via a sample-transport system. A large air-handling system maintains all the glove-box enclosures and the transport system at a negative pressure relative to the room pressure. Scrubber units, incorporated in the air-handling system, clean the air prior to its release to the atmosphere.

Processing of a sample begins at the crusher box (Fig. 2), in a heavily shielded compartment where incoming samples are initially stored in a movable, six-position sample tray. Upon demand, the tray moves to a position below the access door located on the floor of the crusher box and delivers one of the samples to the crusher box. Once a sample is in the crusher box and the access door is closed, the tray containing the remaining samples returns to its original position in the shielded compartment.

The sample in the crusher box is weighed, transferred to a small steel cup, and then crushed in a hydraulic press. The use of a hydraulic press for the crushing operation offers

major improvements over our past procedure of crushing the samples by hand using a mortar and pestle. The new procedure provides smaller and more uniformly sized particles, thereby increasing the surface area and allowing better contact with the HF used in the chemical processing. This step not only gives us better control over the very exothermic chemical reaction that occurs upon addition of the acid but also has the advantage that the rate of dissolution increases with decreasing particle size. Thus, we now achieve a more uniform sample than before and, at the same time, reduce the sample handling and, thus, the radiation dose to the hands of personnel.

After being crushed, the sample is transferred to a platinum crucible and placed in the sample-transport system for delivery to one of the 12 glove boxes used for chemical processing. The sample-transport system is another improvement over the old system: it allows the entire sample-processing operation to be carried out in a totally enclosed system. Previously, samples were hand carried between processing stations by dissolver personnel.

Figure 1. A top-view schematic diagram of the dissolver facility.

This open-air transport was further complicated in that dissolver personnel had to wear respirators because of the possibility that gaseous fission products (such as radioiodine) might evolve from the samples during the transfer. With the new transport system, we again reduce the radiation exposure associated with handling the samples, and the samples are always contained under a controlled atmosphere from the time they are opened until the dissolution process is complete.

An electronic chassis, mounted on the top of the crusher box, controls all operations associated with the hydraulic press, the sample-delivery system, and the transport system. Dual, interlocked hand controls for the hydraulic press and door-interlock switches for the transport and the sample-delivery systems protect personnel from moving mechanisms. In addition, the microprocessor-controlled, stepped-motor-driven transport system incorporates light-sensitive position detectors and fail-safe mechanical switches to precisely control and monitor the location of the crucible.

When a sample has been delivered to one of the 12 glove boxes, the chemical dissolution process is initiated. During the first phase of the dissolution, concentrated HF is pumped into the sample crucible, and the sample is allowed to react with the acid for several hours at a temperature slightly below the boiling point of HF. By this time, about 98 wt% of the sample has been dissolved. The liquid in the crucible is then reduced to near dryness, and repetitive treatments with fuming perchloric acid remove the residual fluoride ions from the sample. The HF-perchloric acid treatment phase

can take up to 8 h, depending on the nature of the sample. The remaining 2 wt% of the sample requires a second dissolving phase that lasts from 2 to 6 h; here, chemical steps similar to those described above are performed by a chemist at each glove box.

Because our ability to deduce device performance depends on measuring certain isotopes of different elements and interrelating these measurements, each diagnostic sample must be dissolved completely. Failure to do so can change the relative amounts of each element in a sample and lead to erroneous interpretations. Therefore, we exercise extreme care in the second phase of the dissolution.

To fully automate the lengthy process associated with the first phase of sample dissolution, we

incorporated the functions of heating, stirring, and weighing into a single module that is controlled and monitored by a microprocessor. Being able to weigh the sample allows us not only to control the addition of acids but also to monitor liquid levels and evaporation rates during the dissolution. We weigh the sample by having the heater assembly on a constant-moment arm that has a linear variable differential transducer (LVDT) attached to it. The LVDT generates an output voltage that is proportional to the displacement. The contents of the crucible are stirred by a Teflon-coated bar that couples to a large, motor-driven magnet located beneath the floor of the glove box.

During the chemical treatment, a fume hood is moved into position above the crucible. The air-handling

Figure 2. The crusher box with its associated electronics. Here, a sample is being loaded into the sample-delivery tray, which is attached to the crusher box.

system removes air from the glove box only through the fume hood; therefore, the noxious fumes produced go directly to one of two acid-scrubber systems. The glove boxes are equipped with a centrifuge and a compartment for storing a sample bottle that will hold the final solution. The centrifuge and sample bottle are used in the second phase of the dissolution process.

Mounted on top of the dissolver glove boxes are five electronic modules that control or monitor the dissolution process, the stirrer, the heater, the centrifuge, and the status of the safety interlocks. Except for the interlock-status module, each unit has been designed to operate either in a manual mode or under control of a master microprocessor located in the dissolution module. In the automated mode, the dissolution module executes the proper sequence of commands to select and pump a known weight of acid, adjust the heater to give the proper sample temperature, evaporate the sample to near dryness, and so on. The microprocessor also monitors

the interlock-status module to sense problems that may occur because of liquid overflow, transport-system failure, or an insufficient glove-box pressure differential. In such cases, the microprocessor triggers an audible alarm and executes a procedure that safely terminates the dissolution process.

The air handling system for the facility consists of two commercially available acid scrubbers (Fig. 3), 12 electrostatic precipitator tubes, an exhaust fan (located on the roof), and associated plumbing.

One of our concerns in designing the air-handling system was to ensure the removal of perchloric acid from the air stream before its

release to the atmosphere.

Perchloric acid differs from most acids in that, as a gas, it behaves as a particulate and is not efficiently removed using conventional treatment with caustic sodium hydroxide. Although we purchased the scrubbers because of the manufacturer's claim that their unique design removes perchloric acid at greater than 99% efficiency, we nevertheless chose to follow the scrubbers with the electrostatic precipitators.

The precipitators shown in Fig. 4 consist of thick-walled carbon tubes through which a centered platinum electrode is placed. During operation, the platinum electrode is held at a +30-kV potential relative to the outer carbon walls. Under the potential gradient, the particulates ionize, and the resulting ions are removed by migration toward the outer wall. An electronic panel controls all functions of the air-handling system, including the pressure differential in the lines, the pump for the chemical-feed tank (which maintains the correct concentration of sodium hydroxide in the scrubber solution), and the power supplies for the precipitators.

Summary and Status

With the installation phase complete and the testing phase nearing completion, we are writing the documentation and operational safety procedures that are required prior to operating the facility. Once it becomes operational, the new facility will increase our capacity to handle radioactive samples and will substantially increase the level of safety for sample handling. We expect the new facility to go into routine operation by the beginning of FY 1990.

Figure 3. The dual scrubber systems and the backside of some of the chemical-processing glove boxes.

Figure 4. One of two racks that support six electrostatic precipitators each.

Upgrade of the Nuclear Chemistry Division's Computer-Based Office Equipment

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The computers used in the Nuclear Chemistry Division for administrative and office computing comprise a heterogeneous collection of many proprietary systems designed to meet many different needs. A long-standing problem has been our inability to transfer and share information among these different systems. In addition, we use hardware and software resources inefficiently because there is little or no sharing of these resources among the different systems.

Our computer needs fall into three categories: analysis of scientific data, office and administrative support, and personal computing. Digital Equipment Corporation (DEC) VAX computers are used to analyze scientific data; NBI word processors, Data General (DG) Comprehensive Electronic Office (CEO) computers, and Unix-based systems are used for office and administrative support; and personal computers (IBM PCs, Apple Macintoshes, etc.) are used for desktop computing. These systems are connected within the Division by three separate networks for Secret Restricted Data (SRD), Protect as Restricted Data (PARAD), and unclassified security environments.

Most scientific and administrative computing uses the unclassified Ethernet standard network, which is our largest and most comprehensive network. Originally, networks permitted communications only among computers from the same manufacturer ("closed" networks). With the Ethernet standard, it is possible to transfer information among many

different computers ("open" networks). Users can now transfer files, share files and software, share printers, send electronic mail, and establish remote terminal connections among numerous systems. We have installed the Ethernet throughout our three buildings and have connected some of our unclassified systems to it.

The NBI system is used by our administrative staff for technical word processing because of its capability to manipulate mathematical equations. A continuing problem has been the inability to transfer word-processing files from the CEO system, which is used primarily by the scientific staff, to the NBI word processors. In addition, both the NBI and CEO systems are proprietary, closed systems that are becoming obsolete.

We have developed a plan for replacing these systems and connecting the Division's administrative staff and users of personal computers to an appropriate network. Our challenge was to find ways to combine our heterogeneous collection of computers and our old operating systems into a new network

that would allow extensive information exchange and resource sharing and, at the same time, provide flexibility for future changes in computer technology.

Computer Integration Plan

We developed a phased transition plan to replace the NBI and CEO systems with suitable hardware and software, address the issue of connectivity between the new systems and the remaining systems, and allow the Division to incorporate future changes in hardware and software with less disruption and less cost. According to the plan, all future computer systems purchased for the Division will adhere to the Open Systems Interconnection (OSI) reference model. This model is a framework that accommodates many network protocols and combinations of protocols with a consistent set of standards leading to interoperable, multivendor computing and communications systems. This model is useful because it specifies seven discrete levels at which two systems can communicate (Table 1). The lowest level defines the physical medium's voltages and timing

Table 1. Functions of the seven-layer OSI model.

Application layer	Electronic mail, file transfer, network management.
Presentation layer } Session layer	Manage communications among computers.
Transport layer	Data become bits or vice versa.
Network layer	Bit reading.
Data-link layer	Physical description of bits.
Physical layer	Cables, wires.

relationships by means of cables. At higher levels, increasingly more complex services are performed. The advantage is that the implementation at any level can be changed without affecting any higher or lower level. By adhering to the OSI model, the Division will be able to procure commercial equipment without being concerned whether it will work with in-place equipment and systems.

Our transition to this new system should be an evolutionary process for several reasons. First, there is a learning process—we must evaluate replacement hardware and software to determine if they meet our needs; second, not everything we need currently adheres to the OSI model; and third, a full-scale change all at once is expensive and difficult to achieve.

With these issues in mind, we developed a phased transition plan

for replacing some of the current systems and integrating the others. We have begun this process with the acquisition of several Sun workstations. We purchased a Sun 3/60 to function as a network file server (i.e., it provides disk-file services for other systems on the network). We also purchased a diskless Sun 3/50 to evaluate the use of diskless workstations by the administrative staff.

Sun Microsystems is an industry leader in the implementation of the OSI concept. So integral are the concepts of openness and interconnectivity to Sun's strategy that Sun has developed a so-called "Open Systems Network" that makes the network and the attached computing resources indistinguishable from a user's personal workstation. Part of this environment is Sun's Network File System (NFS), which allows access to an original file residing

anywhere on a multivendor network without explicitly having to copy it onto the user's machine. This gives a single-file consistency in multivendor, distributed environments that was once available only on time-sharing systems from single vendors.

In addition to the Sun workstations, we have acquired hardware and software to begin connecting some IBM PCs and Macintoshes to the network. Sun's NFS allows PCs to share information and resources with other machines on the network. We can now back up a PC disk over the network to the disks attached to the Sun 3/60 file server. We have also connected the AppleTalk networks to the Ethernet network, and with the necessary software, we are able to communicate between the Macintoshes and the PCs. The PCs can now use the PostScript-compatible printers attached to the AppleTalk network. All of this has been accomplished within the Open Systems Network environment (Fig. 1). We also are exploring and evaluating ways to replace the functions of the CEO system and to replace the NBI workstations.

Summary

We believe this plan will accomplish the goal of optimizing the use and connectivity of existing personal computing equipment while giving our office and administrative functions improved capability and performance. The transition from proprietary, semiconnected systems to open systems will give the Division the desired connectivity and more flexibility in the future. With any new system that follows the OSI reference model, electronic communication among the scientific, administrative, and secretarial staffs will become a reality.

Figure 1. The Open Systems Network makes connectivity possible for all unclassified Nuclear Chemistry Division computers.

Drillstring Gas Sampling

C. F. Smith

With varying degrees of success, we have collected gas samples from postshot reentry drill holes for nearly 25 years. Typically, we inserted a 2-in.-diam tube, perforated near the end, into the drill hole after we collected sidewall core samples. Often, we sealed the core hole to avoid collecting gas from the thermally hot "puddle" region at the bottom of the cavity and drilled a special sidetrack hole for gas sampling. Once the tubing was emplaced, drillers packed off and cemented the annulus between the tube and the hole wall.

After the drill rig was removed, the sampling crew connected pumping equipment to the tubing, drew gas, and collected samples. When the tube was fixed in space, we could shorten it explosively, if necessary, but otherwise, we could not vary its position to control sample quality. Normally, samples were poor at first, improved in time, and ultimately deteriorated. On occasion, either an on-line or a grab-sample analysis capability was fielded, but these systems proved ineffective because we had no control over sample quality. Gas fractionation was a persistent problem inherent in the underground transport mechanisms that brought gases to our sampling inlet.

The sampling operation was expensive. Drilling of the sidetrack hole, the cost of the hardware, the manpower to emplace the tubing, and the extended sampling period could escalate the operating costs to several hundred thousand dollars per event. Clearly, an alternative was needed. For many years, prompt gas sampling provided

samples of better quality, generated more diagnostic information, and promised to obviate the need for drill-hole sampling. We suspended the use of this technique in 1986, primarily because of budgetary constraints. The alternative concept of sampling through the drillstring then became worth considering.

Drillstring Sampling—Historic

Sampling through the drillstring is not a new idea. In fact, at least four events between 1969 and 1972 were so sampled. Results were poor because of limited technical capabilities and many problems with the equipment. On the Jorum Event, we used a dedicated drill hole for sampling but failed to find radioactive gas, although samples were obtained later from a tube placed in the hole. Drillstring sampling on the Yannigan Event also failed, and no samples were obtained. On both the Parnassia and Dianthus events, the results were erratic, and gas quality was often poor and nonrepresentative. Comparisons based on field gas chromatography were used to evaluate the results. Little in the way of useful device-diagnostic information was obtained.

At the time, experimenters were actually more interested in determining the optimum location for a sampling tube than they were in obtaining a definitive suite of samples from the drillstring. The reluctance to rely on drillstring samples appears to have resulted largely from containment concerns. From these experiments, however, we derived our criteria for emplacing tubing in a sidetrack hole (Fig. 1).

Since then, the use of tubing in drill-back reentry holes has been the standard reentry sampling technique.

Drillstring Sampling—Modern

We were motivated to revive the idea of sampling through the drillstring by our desire to have some control over the location of the gas inlet during sampling. We wanted to determine the quality of the gas being collected and to obtain samples 2 to 3 d after the shot, rather than wait 7 to 10 d for completion of coring. We also recognized that early collection of representative samples would often suffice. In this case, the expense of tubing emplacement could be avoided.

Figure 1. Typical reentry drill-hole trajectories for LLNL and Los Alamos. Sampling was attempted at various depths, along the paths shown, inside the projected chimney region (see Table 2). Both trajectories enter the chimney at an elevation significantly above the traditional tubing-emplacement location used by LLNL for gas sampling in a side-track hole.

Reentry drilling is directed toward the region deemed appropriate for core sampling. Our operation begins once drilling penetrates the projected chimney, as shown in Fig. 1. The hole is drilled past this point to provide a sump for the drilling mud. We then retract some pipe sections in an attempt to raise the inlet port above the fluid in the hole. We can remove additional pipe sections or drill deeper and retry, if necessary, to obtain the desired samples.

At the top of the drillstring, our gas-sampling head is joined to the drill pipe. This head is simply a valve that closes the pipe above a side arm where our gas-sampling hose is connected. Above that is a containment fixture connected to the drilling-mud line that will flood the

pipe, if necessary, to ensure containment of any radioactive gas. The hole annulus can also be flooded with mud. The plug, which closes the sampling port near the bottom of the drillstring, can then be pulled. Once the port is open, the mud in the pipe runs into the hole, leaving the pipe ready for sampling.

Figure 2 is a schematic of our surface equipment. We install hoses from the drillstring through a compressor to a disposal well (i.e., to the annulus of the hole being drilled or to another reentry hole nearby). A sampling loop branches from the main loop and runs through our analysis and pumping trailers. Excess gas is collected in buried containment tanks. Four evacuated pumping tanks (3.8 m^3 each) are available to rapidly exchange gas in

the drillstring through the main loop. Each loop operates independently and has its own monitors. All facilities, except the buried tanks, are moved to the site, set up, made operational, and leak-checked after the shot.

Our analysis trailer contains a quadrupole mass spectrometer and a gamma-ray spectrometer. A third trailer houses the computers to operate the spectrometers, the control system for the pumping trailer, and the system monitors. During pumping, we can observe gas composition, pressure, flow rate, radiation level, and radioisotope concentration on our monitors. When the on-line analyses indicate the presence of good-quality gas, we collect a sample. Occasionally, gas quality gradually improves, and additional samples are obtained. Once the gas quality has stabilized, a few additional samples are taken to complete the desired suite.

In concept, our current technique is not much different from that used previously. However, our drillstring connection is less likely to leak air into the sample line, and our new pumping system is significantly better. The use of pumping tanks to move gas rapidly is also a distinct improvement, as are our on-line analytical capability, our experimental design, and our modern analytical tools.

Experimental Results

Table 1 summarizes our recent experiments. All of these events were emplaced in volcanic tuff of similar density. Sampling was done 2.5 to 3 d after the shot.

Table 2 summarizes our experience at each of the sites. The number of sampling attempts is indicated for each, together with the true vertical depths of both the bottom of

Figure 2. Surface equipment used by LLNL for drillstring sampling. Connection to the drillstring is accomplished by a special gas-sampling head. Compressors or pumping tanks pump gas through the main loop, and excess gas is sent either to the hole annulus or to a nearby reentry hole. The side loop passes through our analysis trailer, where mass and gamma-ray spectrometers provide real-time concentration data. Samples are collected at the pumping trailer, and gas continues through the side loop into buried tanks. Operations are monitored and controlled from the control trailer.

the hole (BOH) and the inlet port. These depths are given relative to the depth of burial (DOB) and have been adjusted for the difference in elevation between the drill pad and surface ground zero. The results of each trial are noted in the table.

Our initial sampling attempts were well up in the chimney, a choice based on our experience with emplaced tubing. These were all sealed, presumably because the inlet was beneath the level of drilling mud in the hole. By raising the elevation of the port above the mud, we obtained flow but did not obtain radioactive gas. Through continued drilling, we eventually found a permeable region of the chimney, which evidently allowed the drilling mud to drain from the hole. Instruments on the drill rig indicated a drop in backpressure in the drilling-mud supply and a higher drilling rate after the breakthroughs occurred. It is surprising that we had to drill so far into the chimney to find such regions. At sampling depths, the hole bottoms were very near the original device location.

Our first attempt was on the Bullfrog Event, and it was a spectacular success. Sampling was attempted both from the drillstring and from the annulus. We obtained five high-quality samples from the drillstring. Gas quality in the annulus was very poor, so we chose not to sample from this source on subsequent events.

Samples obtained on the Texarkana Event were used to obtain ratios of the short-lived fission products—one of the experimental goals. They were not, however, good enough for diagnostics. We suspect, on the basis of later experience, that we simply did not drill deep enough on this event.

Table 1. Recent drillstring sampling in volcanic tuff of similar density.

Event	Event date	Sample date	DOB ^a (m)	Hole desig.	Geologic medium	Density (g/cm ³)
Bullfrog	8/30/88	9/2/88	489.2	4au	Tuff Ranier	1.89
Texarkana	2/10/89	2/13/89	504.3	7ca	Tuff Ash flow	1.90
Kawich	2/24/89	2/26/89	370.3	2cu	Tuff Tunnel beds	1.85
Ingot	3/9/89	3/11/89	500.0	2gg	Tuff Ranier	1.92
Palisade	5/15/89	5/17/89	335.3	4at	Tuff Paintbrush	1.81

^a Depth of burial.

Table 2. Drillstring sampling results.

Event	Trial	Depth/DOB ^a		Result
		BOH ^b	Port	
Bullfrog	1	0.831	0.760	Sealed
	2	0.831	0.724	Flow—no activity
	3	0.914	0.848	5 excellent samples
Texarkana	1	0.854	0.823	Sealed
	2	0.925	0.876	Poor, restricted
	3	0.925	0.841	8 samples
Kawich	1	0.894	0.854	Sealed
	2	0.962	0.924	Sealed
	3	0.987	0.947	5 excellent samples
Ingot	1	0.847	0.785	Sealed
	2	0.881	0.785	Sealed
	3	0.936	0.870	Sealed
	4	0.969	0.932	Flow—no activity
	5	1.041	1.011	2 excellent samples
Palisade	1	0.847	0.752	Restricted flow—no activity
	2	0.925	0.804	Sealed
	3	0.925	0.754	Flow—no activity
	4	1.006	0.754	4 excellent samples

^a Depth of burial.

^b Bottom of hole.

Excellent samples were obtained on the Kawich Event, where the first of the relatively deep holes was drilled. After several attempts to sample were aborted because of the presence of drilling mud in the hole, we decided to drill until a breakthrough occurred. The drillers "sensed" a loss of backpressure and an increased drilling rate when the eventual sampling depth was reached. We have used these indicators to identify sampling depths ever since.

Sampling on the Ingot Event was terminated early because of the presence of steam in the surface plumbing. Samples there contained excess fission-product gases relative to tracer species, and their value was consequently degraded for fission diagnostics. However, these same

samples were excellent for determining some short-lived detector-activation product species. We believe that the steam problems on the Ingot Event were a consequence of placing the inlet port too low in the hole.

On the Palisade Event, we obtained four excellent samples when we drilled to the same relative depth as on the Ingot Event. We did not encounter any steam problems. The difference presumably lies in the fact that we located the inlet port well up in the hole prior to sampling. The Palisade hole was sampled again through the drillstring at the same elevation after coring was completed. The sample suite was acceptable for all of our diagnostic goals. We elected not to require additional sampling and did not

emplace tubing, with a resulting probable savings to the program of \$150,000 on this event.

Summary

Gas samples of excellent quality can be obtained from the reentry drillstring within a few days of the event. For events in tuff, it appears desirable to drill nearly to the working-point depth and then to place the inlet port of the drillstring at an elevation well up the hole. The drilling engineer may well be able to sense a breakthrough when an appropriate depth is reached. Operations are quick, requiring only a few hours once an indication of gas flow is seen. The use of drillstring sampling can preclude the need for emplacement of tubing for sample collection.

Misty Echo Cavity Phenomenology Studies

C. F. Smith

The Misty Echo Event, a phenomenology experiment conducted by the Defense Nuclear Agency (DNA), was detonated in a mined cavity at the Nevada Test Site (NTS) on December 10, 1988. At the request of the DNA, we participated in the experiment to investigate issues of concern to those who design ways to contain detonation-related gases. Our goals were to study the source and composition of the cavity gas and to investigate the quantity of material outside the cavity that contributes volatiles to the cavity.

Knowledge of the composition and origin of the cavity gas is central to the design of containment

features for underground detonations. The cavity gas is the driving fluid and its composition is a necessary input for a variety of calculations. It is also the material that challenges containment. However, our ability to reliably predict the composition is imperfect, at best.

Observations such as those conducted on the Misty Echo Event have only recently been used to address containment concerns. They furnish insight into cavity phenomenology, provide data against which calculations can be compared, and delineate the nature and scope of potential containment issues. Our ability to predict cavity

phenomenology should improve, and modifications to emplacement techniques may be suggested by the results of these experiments.

Experiment Description

The Misty Echo Event was the first nuclear detonation on which we installed a wall-material-incorporation experiment. This novel experiment was an incremental-addition measurement in which we used three sets of gaseous tracers, seven canisters in each, located at intervals in the grouted upper access drift and in the tuff along its right rib. Canister locations are shown in Fig. 1. Each canister was fitted with

a bismuth plug designed to melt at 271°C so that it would release gas when heated. Water was added to the contents, when necessary, to create a positive internal pressure and to ensure release of the canister contents when the plug melted.

The tracer canisters emplaced in the grout column contained neon enriched in ^{22}Ne . They were suspended in the center of the drift from fiberglass rods hung from rock bolts placed in the back of the drift.

Two xenon tracers were emplaced in the tuff, one of which was enriched in ^{124}Xe and the other in ^{136}Xe . These were paired and placed in holes drilled into the rock from the access drift. The neon and ^{124}Xe canisters had a "bulk" density of 1.9 mg/m³, which matched that of the surrounding material. The ^{136}Xe canisters, which were 50% denser than the host tuff, were included as a test of the importance of matching densities in experiments of this kind.

We emplaced three tracer species (^3He , natural krypton, and xenon enriched in ^{129}Xe) in the preshot cavity to facilitate study of the cavity gas. These tracers served as reference materials whose total in the gas was known a priori. Sampling was accomplished through the drill pipe that remained after the DNA completed a reentry hole, extending from the fast-data recording alcove to the chimney region above the detonation point. The hole was 285 m long, sloped upward at a nominal 11-deg angle, and penetrated the chimney 52 m above the plane of the working point. We used this source for a total of eight samples taken from 47 to 130 d after the detonation.

A portable sampling skid was used to collect samples. Components of this skid included a dropout chamber and a drying tube to remove water, a pump to draw fresh

gas to the sampler location, and an evacuated 34-l sample bottle. Prior to each sampling, the lines were purged, and chimney gas was circulated to ensure that gas from the chimney was present at the sampler. The pump was then shut off, and the 34-l bottle was opened. After it filled, this bottle and the associated drying tube were sent to LLNL for processing and analysis.

At LLNL, we processed a portion of each sample, typically 1 to 2 l, by elution chromatography to obtain pure hydrogen, argon, krypton, and xenon. These gases were then subjected to radioassay by beta counting or gamma-ray spectrometry in our counting facilities. Our isotope-ratio mass spectrometer was used to determine the deuterium-to-hydrogen ratio in the hydrogen fraction. The isotopic ratios of helium, neon, krypton, and xenon were determined on our rare-gas mass spectrometer in

fractions obtained by selective desorption from charcoal. Mass spectrometric analyses determined the gross composition and measured rare-gas concentrations using the sample fraction remaining after the reactive gases were chemically removed.

Results

Our analyses showed that the gas was mostly air with about 35% hydrogen. Since air in excess of that present in the preshot cavity can be presumed to have entered the chimney following subsidence, we conclude that the cavity gas was initially nearly all hydrogen in steam. We determined the amount of hydrogen initially present by measuring the total hydrogen present at sampling time (relative to the ^3He tracer) and adding an amount equal to twice the amount of missing oxygen (as judged by argon). This corrected for hydrogen combustion

Figure 1. Plan view of the Misty Echo Event cavity region, showing the locations of the various gas-tracer canisters.

by oxygen in the air that entered the chimney following subsidence. The initial hydrogen total thus obtained was consistent with the amount of reducing material known to be present in approximately 3 m of the cavity wall.

We measured the deuterium content of the hydrogen and found a constant value of 115 ppm. Since the hydrogen in NTS water is 145 ppm deuterium, the implied equilibrium constant for deuterium exchange between water and hydrogen was 1.26. This value is characteristic of an exchange-reaction temperature of 900 K. The high temperature and constant ratio are an indication that the exchange was "quenched" as the gas cooled and did not continue at an appreciable rate thereafter.

The same quenching should pertain to tritium exchange. The corresponding equilibrium constant for tritium exchange between hydrogen and water is 1.3. The amount of water required to dilute the estimated residual tritium to 1.3 times the tritium-to-hydrogen ratio in hydrogen is assumed to be the amount of water existing as steam in the presubsidence cavity. If we assume that the tuff outside the preshot cavity was saturated with water and that the water content of the grout in the cavity invert is similar to that in the tuff, then the indicated release depth is found to be consistent with that deduced from the amount of hydrogen gas.

The tritium-to-hydrogen ratio was also measured in water collected with the gas, and this ratio varied widely. The highest tritium content in the water was one-tenth of that in the hydrogen gas. The samples clearly are not cavity water,

and they indicate the likelihood of late-time influx into the chimney.

The measured amount of ^{124}Xe (relative to the ^{129}Xe tracer) equals that contained in three canisters, indicating gas entry from at least 3.9 m but less than 5.1 m (preshot) into the tuff. The contents of four canisters of ^{136}Xe mixed with the cavity gas, suggesting a maximum depth of 5.7 m. However, the denser ^{136}Xe canisters may well have lagged during cavity expansion, and this greater depth indication is suspect. A value on the order of 5 m appears valid.

Isotopic ratio measurements of ^{22}Ne (relative to ^3He tracer) revealed the presence of tracer gas from four canisters, indicating gas entry to the cavity from at least 4.5 m but less than 5.5 m (preshot) into the grout column. This is consistent with the results from the wall tracers and suggests that no appreciable difference exists between the expansion behavior of the tuff and the grout column.

Near the end of the sampling period, our measurements detected the presence of additional wall and grout tracers. These amounts were small (less than an additional canister) but suggested the possibility of material entering the chimney from the surrounding environment at very late times. We think it is unlikely that adequate mixing took place between these late entrants and the reference tracers, and we believe that any additional interpretation of these measurements would not be meaningful.

Because ^{136}Xe is produced in fission, interpretation of the ^{136}Xe wall-tracer results required knowledge of the device fission yield. The ^{85}Kr fission indicator (relative to the krypton tracer) indicated nominal device performance. The residual ^{136}Xe ,

after the subtraction of exactly four tracer canisters, gave the same result. We can conclude that the yield of the Misty Echo Event was as expected.

Discussion

We used a simple geometric model for comparing the measurements. Assuming that equal volumes of material above and below the plane of the cavity floor contributed volatiles, we obtained a relation between the depth into the wall and the mass of the rock. Our interpretation of results from the wall and grout tracers is that they are integral values, include possible late-time effects, and may be taken as upper limits for the amount present during cavity expansion. We believe that the hydrogen and the tritium-to-hydrogen results more nearly represent the early cavity conditions.

Apparently, the amount of rock releasing water is less than that releasing gaseous species. This result suggests that gas migration into the cavity continued for some time after the hydrogen-exchange equilibrium was quenched by cavity cooling. Since we believe that steam is the carrier that brings the tracer gas into the cavity, we must conclude that at least two, and perhaps three, distinct phases of introduction exist.

Initially, a prompt, high-temperature reactive phase takes place, during which water is converted to hydrogen gas by reaction with reducing materials in the environment, and significant steam pressure drives the cavity growth. There follows a later, lower-temperature, nonreactive phase in which additional steam and liquid water bring environmental gases into the cavity from beyond the cavity boundary. Because we find the tracer gases

introduced during the second phase to be well mixed with the cavity tracers, we believe that both of these phases probably occur before chimney subsidence. Following subsidence, there is a very late-time extension of the second phase, augmented by gaseous diffusion. This

late-time influx is not necessarily mixed with the cavity tracers and is, therefore, difficult to quantify.

Conclusion

In conclusion, we note that all of the depth indications determined in these measurements exceeded the

expectations of many experimenters. Our results, therefore, have been received with a good deal of interest by the community at large. We will repeat these experiments on future events to both confirm and augment the implications of our Misty Echo Event investigations.

Reliability of Actinide Tracers

R. W. Lougheed, R. J. Dougan, and A. A. Delucchi

We analyze the performance of nuclear devices tested underground at the Nevada Test Site by measuring the quantity of individual nuclides in postshot drillback samples. To calculate the total amount of the measured nuclides produced by a nuclear device, we need to know what fraction of the device or device part (bomb fraction) our sample contains. To measure this fraction, we place known amounts of actinide nuclides (bomb-fraction tracers) inside or outside the nuclear device.

In this article, the emphasis is on the reliability of external bomb-fraction tracers, although most of the factors that affect the reliability of external tracers also apply to internal tracers. We use external bomb-fraction tracers in three principal ways: to trace either the whole device or a part of the device, to measure the activation products of elements placed with the tracer, and to determine the chemical fractionation or volatility of other elements.

Measurement Technique

We use the nuclides ^{233}U , ^{235}U , ^{236}U , ^{237}Np , ^{238}Pu , ^{242}Pu , ^{241}Am , and ^{243}Am , and ^{244}Cm as external bomb-fraction

tracers. (Table 1 lists these tracers and their frequency of use from 1979 through 1988.) The use of bomb-fraction tracers is similar to the use of radioactive tracers in ordinary chemical procedures to determine chemical yields. There is an important difference, however, in that we often use the bomb fraction measured from a nuclide of one element to deduce the recovery of nuclides of other elements. For example, if we measure a bomb fraction of 1×10^{-14} for ^{241}Am in a particular sample, we might then divide the measured amount of another radionuclide in that sample (e.g., 1×10^6 atoms of

^{89}Zr) by the ^{241}Am bomb fraction to arrive at a total of 1×10^{20} atoms of ^{89}Zr produced by the device.

The reliability of this technique depends on three conditions: the same relative underground chemical behavior of the tracer and the traced element (no chemical fractionation), accurate pre- and postshot assays of the tracers, and good physical mixing of the tracer and the traced nuclides either before or during the nuclear explosion. Considering the enormous energy released in a nuclear device, one would expect good mixing of the device debris, but if elements are not mixed or placed together prior to detonation, mixing is frequently incomplete. We will not discuss mixing further in this article but will concentrate on the other two conditions for reliability.

The empirical observation that a large number of elements recovered from postshot samples are seldom chemically fractionated from each other permits us to make meaningful radiochemical measurements by using bomb-fraction tracers. These elements, all of which are thought to exist in compounds with high boiling points (hence, called refractory

Table 1. A summary of external tracer usage from 1979 through 1988.

Tracer	No. of times used	Typical amount per use (g)
^{233}U	54	20–300
^{235}U	1	200
^{236}U	2	250
^{237}Np	5	20
^{238}Pu	3	4–20
^{242}Pu	41	10–20
^{241}Am	27	5–20
^{243}Am	1	1
^{244}Cm	47	0.5–2

elements) during condensation underground, are scandium, yttrium, the rare-earth elements, hafnium, tantalum, thorium, protactinium, neptunium, plutonium, americium, and curium. A few elements that are chemically fractionated relative to this refractory group are beryllium, vanadium, manganese, niobium, and uranium. Therefore, all of the actinide tracers listed here, except uranium, are considered to be refractory in the underground environment and, hence, should be interchangeable for use as bomb-fraction tracers.

We use uranium isotopes (usually ^{235}U) as bomb-fraction tracers paired with one of the refractory actinide tracers (usually ^{242}Pu) to measure the chemical fractionation of uranium from the refractory elements. The recoveries of the uranium and refractory tracers are used to generate a correction factor (CORU) that we apply to other postshot uranium data. Implicit in this

correction is the assumption that all uranium nuclides in a postshot sample have the same chemical fractionation relative to the refractory nuclides, regardless of their preshot location. This assumption has been validated by the internal consistency we have obtained after applying the CORU factors to uranium data.

We also use the CORU measurement as an indicator of possible fractionation effects with elements other than uranium, even those elements normally considered to be refractory. On the basis of the consistency of results from samples with different CORU factors, we suspect that even the refractory elements may chemically fractionate to some extent in samples that are very depleted or enriched in uranium relative to the refractory tracers. Accordingly, we normally attempt to obtain postshot samples that are between about 10% enriched and about 30% depleted in uranium relative to the refractory tracers. Sometimes, however, we

may have a few samples for analysis that are highly depleted in uranium (30 to 50%), or perhaps such samples are all we can get.

Results

We now discuss the results of a series of experiments in which several actinide tracers were loaded together in underground nuclear tests, and measurements were made of the relative recoveries of these tracers in postshot samples. Our purpose was to see if any differences in recovery were the result of chemical fractionation or systematic measurement errors and, specifically, if these differences occurred in samples with moderate or high chemical fractionations of uranium relative to the refractory elements.

Tracer Recoveries from Normal Postshot Samples. Table 2 summarizes tracer-recovery results from nine experiments that had paired-actinide tracer loadings. These results were obtained from samples that met our usual acceptable range of uranium chemical fractionation; results from some samples that were highly depleted or enriched in uranium are discussed separately.

The results given in Table 2 indicate that equal amounts of neptunium tracer were recovered relative to plutonium, and of americium relative to curium. However, americium and curium had about a 5% higher recovery than neptunium and plutonium. A previous study that compared pre- and postshot ^{241}Am and ^{239}Pu from device parts did not show any systematic difference in americium and plutonium recoveries (J. Wild, Lawrence

Table 2. A summary of bomb-fraction ratios from paired-tracer loadings for samples with normal uranium chemical fractionation (+10 to -30%) relative to a refractory actinide tracer. The results are typically the average of six samples.

Event	Average bomb-fraction ratio			
	$^{241}\text{Am}/^{242}\text{Pu}$	$^{244}\text{Cm}/^{242}\text{Pu}$	$^{244}\text{Cm}/^{241,243}\text{Am}$	$^{237}\text{Np}/^{242}\text{Pu}$
A	1.06	1.04	0.97	—
B	—	1.06	—	0.99
C	1.03	1.06	1.03	1.02
D	1.04	1.10	1.06	1.03
E	—	—	0.97 ^a	—
F	—	—	1.02	—
G	—	1.05	—	—
H	—	1.01	—	—
I	—	—	1.00	—
Avg.	1.04 ±1.3%	1.05 ±2.7%	1.01 ±3.2%	1.01 ±1.6%

^a The isotope ^{243}Am was used.

Livermore National Laboratory, private communication, 1979). For 19 events, that study reported a $^{241}\text{Am}/^{239}\text{Pu}$ recovery ratio of $1.011 \pm 4.1\%$. Given the experimental uncertainty of the former study, the result is not inconsistent with the 5% bias observed in the current experiments. Systematic errors in the pre- or postshot assays of the tracers could lead to such apparent recovery biases. The results of recent analysis of the ^{242}Pu and ^{244}Cm tracers are discussed below under Accuracy of Tracer Measurements. The individual sample results (not shown) for the data summarized in Table 2 were internally consistent and did not reveal any significant chemical fractionation among the actinide tracers.

Tracer Recoveries from Highly Chemically Fractionated Samples. We expect that chemical-fractionation effects in a sample will be revealed by a change in the elemental recovery ratios that is correlated with uranium chemical fractionation in the sample. An examination of individual samples that are very depleted or enriched in uranium shows a somewhat different picture from that for samples with moderate fractionation effects. In the paired-tracer experiments, we attempted to select samples that had a wide range of uranium chemical-fractionation values. Because of sampling limitations, we obtained such samples on only a few events. We did obtain samples from Event A with enrichment of uranium up to seven times that of plutonium. These samples did not indicate any chemical fractionation between americium and curium, but they did indicate that plutonium is slightly volatile

relative to americium and curium, as shown in Fig. 1. The cluster of points near a $1/\text{CORU}$ value of 1 are those samples we would ordinarily choose for device diagnostics. We also learned from the Event A samples that the activation products from rare earths and zirconium behave the same as those from americium and curium and, therefore, plutonium was also slightly volatile compared with these device-produced radionuclides. One highly uranium-enriched sample from Event C also indicated that plutonium was somewhat volatile compared with americium and curium and that neptunium was enriched relative to plutonium. We were not able to obtain samples from these events that were highly depleted in uranium.

From the results shown in Table 2, it appears that neptunium and plutonium do not chemically fractionate from each other. However, other evidence, including the uranium-enriched sample obtained from Event C, shows that neptunium does chemically fractionate from plutonium. Measurement of the ratio of ^{236}Pu (which is present as ^{236}Np during condensation of the fireball) to ^{238}Pu (which is, in some events, made in the same device part as the ^{236}Np) vs CORU clearly shows that neptunium is more volatile than plutonium. An example of this is shown in Fig. 2. Note that this sample set includes several samples that are highly depleted in uranium relative to the refractory tracer and that neptunium is depleted relative to plutonium. Similar analyses from other events support a depletion of neptunium relative to plutonium in uranium-depleted samples.

Accuracy of Tracer Measurements. To check for a possible bias in the quantitative determinations of preshot ^{242}Pu and ^{244}Cm loadings, we have examined the accuracy of our tracer-analysis methods. We used two different methods to determine the preshot amounts of the two tracers. The quantity (weight) of ^{242}Pu was determined from the

Figure 1. Event A: ^{241}Am and ^{242}Pu volatility vs uranium depletion ($1/\text{CORU}$). Similar results were obtained with ^{244}Cm and ^{242}Pu .

Figure 2. Relative neptunium and plutonium volatility vs the correction factor for uranium depletion (CORU).

weight of the loaded plutonium oxide and the measured ratio (by weight) of ^{242}Pu /oxide. We checked the accuracy of this conversion ratio by dissolving weighed fractions of ^{242}Pu /oxide and determining the amount of ^{242}Pu in each by mass spectrometry. The new value of 0.780 ($\pm 1.8\%$) was within 1σ of the previously determined value of 0.790.

We determined the amount of ^{244}Cm in a tracer set by using calorimetry. The heat output of the completed curium tracer set was measured, and a ^{244}Cm conversion factor of 2.830 W/g was used to determine the ^{244}Cm content. This value assumes no contribution from other heat-emitting nuclides. To check this assumption, we analyzed a sample of our curium oxide, using radiochemical techniques, for other heat emitters. We found that less than 0.15% of the heat comes from nuclides other than ^{244}Cm (primarily from ^{240}Pu , the alpha-decay daughter of ^{244}Cm). In addition, we compared the ^{244}Cm content of the sample as determined through calorimetry with the value determined through radiochemical analysis. The two methods agreed within 1%.

Thus, we have found no evidence for any significant errors in the preshot quantitative analysis of either the ^{242}Pu or the ^{244}Cm tracer sets, and we know of no systematic biases that can explain the 5% differences in recovery for americium and curium relative to plutonium and neptunium observed in the tracer-recovery experiments.

Conclusions and Discussion

The paired-tracer experiments for samples where uranium and the refractory tracer are only slightly fractionated gave similar recoveries, except that we observed an unresolved 5% bias between ^{242}Pu and ^{237}Np relative to ^{241}Am and ^{244}Cm . We observed that plutonium was slightly volatile relative to americium and curium in samples that were highly enriched in uranium. We could not confirm that the observed enrichment of plutonium relative to americium and curium in uranium-enriched samples was matched by a corresponding depletion of plutonium relative to americium and curium in samples that were highly depleted in uranium. However, we cannot exclude the possibility that this 5% bias was caused by chemical fractionation of plutonium from americium and curium. This would be inconsistent with the traditional assumption that the refractory elements are not chemically fractionated from each other if they are not highly fractionated from uranium. We did confirm that neptunium is more volatile than plutonium in both uranium-enriched and -depleted samples, that the recoveries of neptunium and plutonium are well correlated in uranium-depleted samples, and that neptunium chemical fraction effects are observed in our normal sample range ($\leq 30\%$ uranium depletion). We conclude that, if we have the choice, we should avoid selecting samples that are very depleted or enriched in uranium relative to the refractory elements.

Future studies and experiments that could help us to understand and interpret chemical fractionation of the actinide tracers and other elements in drillback samples might include an examination of the historic data base for evidence of chemical fractionation among all refractory elements. We need to learn more about the influence of the underground environment on post-shot samples. Oxygen and steam pressure influence the formation of volatile species. The geologic medium, water content, and even the large amounts of iron associated with the device canisters may reduce the oxygen content and, hence, the chemical species formed when the device debris condenses. We could chemically study our post-shot samples to determine the actual condensed species that contain the radionuclides we measure. Measurements of the thermodynamic properties of volatile tracer compounds and the condensed species could help in predicting chemical fractionation and selecting good diagnostic samples.

In summary, although good results have been obtained from the analysis of most drillback samples, we need more knowledge about the underground chemistry of nuclear-device species before we can interpret and correct chemical-fractionation and systematic-recovery differences in all of the drillback samples we obtain.

Uranium Fission Product Yields

D. R. Nethaway

In a previous article,¹ I described a program to develop a complete set of uranium fission product yields for use in Test Program diagnostics. In the past, we have depended on using yields from fission of only ^{235}U and ^{238}U with fission-spectrum and 14-MeV neutrons. Even though most of the uranium fission in a nuclear device is from these two isotopes, we need to treat the other isotopes of uranium as well, and at all energies from 0 to 15 MeV. Yields have been measured for many high-yield products from fission of ^{235}U and ^{238}U from 0 to 9 MeV and at 14 MeV. Although the data tend to scatter, some yields are sufficiently well known over the entire energy range of interest. This is true, for example, for some fission products that we routinely measure such as ^{95}Zr , ^{144}Ce , ^{147}Nd , and ^{156}Eu .

However, for others such as ^{85}Kr , ^{136}Xe , and ^{161}Tb , there are no data for energies between fission spectrum and 14 MeV. (Note that "fission spectrum" denotes a wide range of neutron energies. I use 1.8 MeV as an equivalent value for the mean energy.) For the fission of ^{234}U and ^{236}U , there are some data for fission-spectrum and 14-MeV fission, and for ^{237}U and ^{239}U , there are no data at all.

Despite the paucity of data in the previously reported study, I interpolated and extrapolated, using French curves with abandon, and produced a preliminary set of fission product yields¹ for ^{95}Zr , ^{99}Mo , ^{144}Ce , ^{147}Nd , ^{156}Eu , and ^{161}Tb from fission of $^{233}\text{--}^{240}\text{U}$. I also decided, however, that it would be worthwhile trying

to find a better method of doing the interpolation and extrapolation, and that is the subject of this report.

Modeling Mass-Yield Curves

Musgrove and coworkers² and Dickens³ developed a method of modeling fission product mass-yield curves based on work done earlier by Crouch.⁴ They showed that a double-humped, mass-yield curve can be represented by the sum of five Gaussian distributions, two for each peak, plus one in the center. They further assumed that the two peaks are identical; that is, Gaussian 1 = Gaussian 5, and Gaussian 2 = Gaussian 4, and that the peaks are symmetric about the mean mass, A . The yields are normalized to 200% with $N_3 = 2(1 - N_1 - N_2)$, where N_i is the area under the respective Gaussian. The use of these assumptions reduces the number of free parameters from 15 to 8. Thus, the yield of a particular mass number, $Y(A)$, is given by:

$$Y(A) = N_1(\alpha_1/\pi)^{1/2}\{\exp[-\alpha_1(A - \bar{A} - D_1)^2] + \exp[-\alpha_1(A - \bar{A} + D_1)^2]\} + N_2(\alpha_2/\pi)^{1/2} \times \{\exp[-\alpha_2(A - \bar{A} - D_2)^2] + \exp[-\alpha_2(A - \bar{A} + D_2)^2]\} + 2(1 - N_1 - N_2) \times (\alpha_3/\pi)^{1/2}\exp[-\alpha_3(A - \bar{A})^2], \quad (1)$$

where $\bar{A}$ is the mean mass, D_1 and D_2 are the distances of the Gaussian centers from $\bar{A}$, and α_i are related to the width parameters σ_i by $\alpha_i = 0.5\sigma_i^{-2}$. This model obviously averages over any fine structure in the

data, but it is quite suitable for duplicating general features of the mass-yield distribution in low-energy fission. As an example, Fig. 1 shows the data and calculated distribution for 14-MeV fission of ^{235}U . The data are from an evaluation for ENDF/B-6 by Rider and England.⁵ The overall fit to the data is very good.

I used a computer program to do a weighted least-squares fit to all of the fission product yield data for uranium fission. My data base consisted of sets of yields for the following types of fission: ^{233}U (thermal, f.s., and 14), ^{234}U (f.s. and 14), ^{235}U (thermal, f.s., 6.0, 7.1, 8.1, 9.1, and 14), ^{236}U (f.s. and 14), and ^{238}U (1.5, f.s., 2.0, 3.0, 3.9, 5.5, 6.0, 7.0, 8.0, 9.1, and 14), where the energies are in MeV, and f.s. refers to fission spectrum (1.8 MeV). All of the thermal, f.s., and 14-MeV yield data are from recent evaluations^{5,6}; the rest are measured yields from the literature.⁷⁻¹⁴ First, I did a least-squares fitting to Eq. (1) for each of the 25 types of fission. My intent in the following steps was not necessarily to use the best values of the eight parameters for each case but to look for systematic trends with uranium mass number and neutron energy in the parameters, so that I would be able to predict the values of each parameter for other types of fission (i.e., the fission of each isotope of uranium between ^{233}U and ^{240}U from 0 to 15 MeV).

I started by picking an average value of 0.0029 for α_3 because it was reasonably constant for all of the types of fission. (The parameter

α_3 is well determined only for 14-MeV fission because it represents the width of the central Gaussian, which increases rapidly in area with excitation energy.) I then repeated all of the 25 least-squares fits, holding α_3 fixed at the average value. For the second step, I plotted $\bar{A}$ vs the neutron energy, E_n , for each uranium isotope. The shift in $\bar{A}$ mimics and is consistent with the change in neutron emission with energy. After obtaining systematic equations for $\bar{A}$ vs E_n , I again repeated all of the least-square fits holding $\alpha_3 = 0.0029$

and the new values of $\bar{A}$ fixed. I repeated this procedure, treating a new parameter each time, until all eight parameters were fixed and determined as functions of neutron energy and uranium mass number. Three parameters, α_1 , D_1 , and D_2 , were found to be functions of neutron energy only, while α_2 , N_1 , N_2 , and $\bar{A}$ are functions of both energy and uranium mass number. The parameter α_2 is not well-determined at intermediate energies and is only weakly dependent on the uranium mass number. The final set of

parameters was used for the calculated curves shown in Fig. 1. Total chain yields for any mass number from fission of $^{233-240}\text{U}$ with neutrons from 0 to 15 MeV can now be estimated using this set of parameters.

Discussion

I prepared a table listing the total chain yields calculated for masses 74 to 161 from fission of $^{233-240}\text{U}$ at 1-MeV intervals from 0 to 15 MeV. It is instructive to compare calculated yields with the data in order to see how good the agreement is. Figure 2 shows the yields of ^{95}Zr , ^{144}Ce , ^{147}Nd , ^{156}Eu , and ^{161}Tb from 14-MeV fission of the various uranium isotopes and shows how the data have been extended to uranium masses 237, 239, and 240. The trends shown by the calculated yields are not necessarily the same as would be constructed with a French curve or other fit to the data because of the averaging effect in doing least-squares fits to a much larger body of data. However, the yields predicted for fission of $^{237,239,240}\text{U}$, shown in Fig. 2, appear to be reasonable.

Figure 3 shows the yields of ^{156}Eu and ^{161}Tb from fission of ^{235}U and ^{238}U as a function of neutron energy. The calculated yields for these products show the expected initial rapid increase with energy, with a change in slope at around 5 or 6 MeV, probably related to the onset of second-chance fission. The agreement between calculation and data is only fair, even considering the scatter in the data and the likelihood that the uncertainty in the data is underestimated. These are low-yield products and difficult to measure, especially at the intermediate energies. The uncertainty in the calculated values is difficult to estimate and is not shown. It may be necessary to scale some of the calculated

Figure 1. Mass-yield curve for fission of ^{235}U with 14-MeV neutrons. The blue line was calculated from the final set of parameters obtained from the least-squares fits of all the $^{233-238}\text{U}$ data using the five-Gaussian model. The five individual Gaussian curves and the input data are also shown.

yield curves to the measured data for the best interpolation. Such a case is shown in Fig. 3b, where all of the ^{161}Tb data lie below the calculated values.

Summary

I have developed a preliminary set of eight parameters that determine a five-Gaussian representation of mass-yield curves for uranium fission. The parameters vary smoothly with uranium mass number and neutron energy, so that mass-yield curves can be estimated for fission of essentially all uranium isotopes with neutrons up to 15 MeV. Although I have only partially surveyed the results of this study so far, I think that the use of such calculated curves will help us estimate unmeasured fission product yields from uranium fission with more confidence. Also, and perhaps most important, the systematics developed here for uranium will help considerably in repeating this study for the isotopes of plutonium, where fewer experimental data exist.

Figure 2. Calculated and measured yields for fission of $^{233}\text{--}^{240}\text{U}$ with 14-MeV neutrons: (a) yields of ^{95}Zr , ^{144}Ce , and ^{147}Nd ; and (b) yields of ^{156}Eu and ^{161}Tb . The trends of the calculated yields are shown by lines.

Figure 3. Calculated and measured yields for (a) ^{156}Eu and (b) ^{161}Tb from fission of ^{235}U and ^{238}U as a function of neutron energy.

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Bismuth Separation from Large Core Samples

F. Bazan and E. M. Delucchi

As part of our research in establishing bismuth as a neutron-fluence monitor for the LLNL Nuclear Test Program, we have developed a radiochemical procedure that isolates trace amounts of bismuth from large core samples.

Several bismuth isotopes are produced by multiple (n,2n) reactions in underground tests. These isotopes are $^{205-208}\text{Bi}$, with half-lives of 15.3 d, 6.2 d, 32.4 y, and 3.7×10^5 y, respectively. Currently, the first three are assayed radiometrically by first gamma-ray counting them in germanium detectors and then interpreting the spectra with the GAMANAL computer code. Mass spectrometry is being used to measure a $^{207}\text{Bi}/^{208}\text{Bi}$ ratio. Also, as part of our studies in developing a procedure, we have extensively used inductively coupled plasma-mass spectrometry (ICP-MS) as an analytical tool to measure the ^{209}Bi mass abundance in solution samples. The extreme sensitivity of this technique makes it ideal to measure nanogram amounts of bismuth, even in the presence of other components of underground debris.

Under normal circumstances, small samples on the order of 0.5 to 1 g of core material (25 to 50 ml of pot solution) are sufficiently large to measure $^{205-207}\text{Bi}$. However, we need larger samples, 10 to 20 g, of core material to measure the ratio of $^{207}\text{Bi}/^{208}\text{Bi}$. Thus, the increase in sample size demands a different type of chemistry that is appropriate

for separating low levels of bismuth activity and microgram amounts of bismuth from high levels of fission and neutron-activated products per gram amounts of dissolved core material.

Procedure

Our new radiochemical procedure is relatively simple and safe for handling 10 to 20 g of radioactive underground debris. Even the dissolution of the original core material does not require special handling; we are presently using our standard dissolving procedure, which consists of a series of treatments with hydrofluoric (HF), nitric (HNO_3), perchloric (HClO_4), and hydrochloric (HCl) acids. The final solution is a 3 to 4M HCl solution containing about 2 g of core material per 100 ml.

Following the dissolution of the core material,

- The sample solution is stirred with an equal volume of isobutyl methyl ketone (hexone) to extract bismuth as an iodo-complex.¹
- Bismuth is back-extracted with 6M HCl.^{2,3}
- Bismuth is adsorbed as a chloro-complex in an anion-exchange resin column.^{2,3}
- Bismuth is eluted with 0.5M HNO_3 .^{2,3}

We first gamma-ray count this low-acid solution to obtain $^{205-207}\text{Bi}$ data and then subject it to further chemistry before analyzing it for the $^{207}\text{Bi}/^{208}\text{Bi}$ ratio by mass spectrometry.

If a chemical yield for bismuth is necessary, we analyze a sample of the original solution and a sample of the 0.5M HNO_3 eluent of the anion column for ^{209}Bi . A ratio of the two determinations gives us a measure of the efficiency of the chemical procedure. At present, chemical yields range from 70 to 80%.

Results

To date, we have processed several 10-g and 20-g samples of underground debris from nuclear events on which bismuth was used as a neutron-fluence monitor. When we counted the samples, we obtained good data for $^{205-207}\text{Bi}$. Low levels of antimony activities were also detected, but they did not interfere with the gamma-ray analyses. The results of gamma-ray counting and ICP-MS have proved this procedure for separating bismuth from large core samples to be reliable, easy, and fast. However, we will continue to study some of the parameters of the extraction step to improve the chemical yields.

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Revision of Bismuth Cross-Section Library Using Improved Treatment of Pre-Equilibrium Neutron Emission

M. N. Namboodiri, M. A. Gardner, and D. G. Gardner

Bismuth is an attractive multiple-order (n,2n) detector for use in the radiochemical diagnostics of underground nuclear tests. We have previously described the calculation of a cross-section set for this detector.¹ We have tested this preliminary cross-section set (Bi986 set) against bismuth detector data from several recent underground tests. These comparisons suggest that the (n,2n) cross sections in the Bi986 set are too low by about 15%, especially for the lighter bismuth isotopes involved. We recognized from the beginning that one possible area of improvement in the calculation was the treatment of pre-equilibrium neutron emission. This recognition occurred because we found that our STAPRE statistical model code predicted very large pre-equilibrium contributions to the neutron emission in neutron-induced reactions on the lighter bismuth isotopes (i.e., ^{204–208}Bi).

Calculational Methods

Recently, we have made certain improvements in the pre-equilibrium calculations in STAPRE. The details of the modifications dealing with the implementation of a spin-dependent exciton model are described elsewhere.² In addition to those modifications, we now allow the state density parameters involved in the modeling of the pre-compound emission process to be supplied as input parameters and also allow the choice of two ways in which to calculate the matrix element, $|M|^2$, for the residual interaction. In this article, we describe these changes and the results of

recalculating the (n,2n) and (n,3n) cross sections for the ground states of ^{204–209}Bi by using the modified STAPRE code.

The usual form³ for the matrix element for the residual interaction is

$$|M|^2 = \frac{k}{EA^3}, \quad (1)$$

where k is a normalizing constant usually derived from data for nearby nuclei, E is the excitation energy, and A is the mass number of the nucleus concerned. A form for k that was also incorporated originally into STAPRE⁴ is

$$k = 0.55 \times 10^{22} \left(\frac{h^2}{2\pi} \right) \left(\frac{4A^3}{20g^3} \right). \quad (2)$$

Upon simplification, this becomes

$$k = 0.115 \left(\frac{A}{g} \right)^3 \quad (3)$$

or

$$k = 0.512 \left(\frac{A}{a} \right)^3. \quad (4)$$

In these equations, g is the single-particle state density, and a is the Fermi gas-level-density parameter, and they are related as follows:

$$g = 6 \left(\frac{a}{\pi^2} \right). \quad (5)$$

If the level-density parameter a reflects collective enhancement and/or other effects of nonsingle particles, it changes rapidly near closed shells and is not appropriate

for precompound calculations. Now, if a is taken to vary smoothly with the A , such as $a = A/8$, a further simplification can be made: $k = 262$, and

$$|M|^2 = \frac{262}{EA^3}. \quad (6)$$

We have found such a smooth prescription particularly useful in the calculation of the precompound reactions on the lighter bismuth isotopes. Fu has noted the same effect.⁵

Results

We have calculated the (n,2n) and (n,3n) excitation functions for the ground states of bismuth isotopes in the mass range from 204 to 209, using the STAPRE code after incorporating the changes in the pre-compound treatment described previously. Figure 1 shows that the pre-equilibrium fractions calculated by using the new prescription are much lower than those obtained by using the original formulation in STAPRE and that they are comparable to those given by the geometry-dependent hybrid (GDH) pre-equilibrium option in the ALICE code.^{6,7}

Experimental information on the neutron-induced reactions on bismuth is essentially confined to the system ²⁰⁹Bi + n. Figure 2 shows the available data on the excitation functions for the (n,2n), (n,3n), and (n,n') reactions on ²⁰⁹Bi, together with the results of STAPRE calculations obtained by using the new pre-equilibrium options. There is good overall agreement between the experimental and calculated excitation

Figure 1. Pre-equilibrium fraction in the neutron emission for ^{206}Bi and $^{208}\text{Bi} + n$ as a function of incident-neutron energy, calculated by using different pre-equilibrium prescriptions.

functions. Figure 3 compares experimental and calculated neutron spectra for $^{209}\text{Bi} + n$ at an incident-neutron energy of 25.7 MeV. The experimental data extend above 12 MeV, and there is good agreement between the calculated spectrum and the data over this energy range, where the most important contribution is from precompound emission. Inclusion of the contributions from direct reactions should remove the difference between the measured and calculated spectra at the highest neutron energies shown in Fig. 3. Such direct-reaction calculations are yet to be done; however, this component amounts to only about 1% of the total neutron spectrum shown in Fig. 3. We also see good agreement between calculated and measured neutron spectra at an incident-neutron energy of 14 MeV (see Ref. 2).

Figure 2. Experimental and calculated excitation functions for $^{209}\text{Bi} + n$.

The calculated excitation functions for the (n,2n) and (n,3n) reactions on the ground states of bismuth isotopes with $205 \leq A \leq 209$ are shown in Fig. 4. Modifications in the pre-equilibrium treatment have resulted in raising the (n,2n) cross sections for the lighter bismuth isotopes by about 15%, while the cross sections for ^{209}Bi are not affected significantly. Thus, the new (n,2n) excitation functions are in better agreement with the conclusions drawn from underground-test data. We have incorporated the newly calculated excitation functions in a new trial cross-section set, together with (n, γ) excitation functions calculated earlier. This new set (Bi389 set) will be further tested by using it to interpret additional test data as they become available.

Figure 3. Calculated and measured energy spectra of neutrons from $^{209}\text{Bi} + n$ at an incident-neutron energy of 25.7 MeV. Black curve = total; blue curve = first nucleus; closed dots = first nucleus precompound; and open circles = data from Marcinkowski and coworkers.¹⁶

Figure 4. Excitation functions for $^{204-209}\text{Bi} + n$, calculated by using STAPRE with the original (blue data points) and new (black curve) pre-equilibrium prescriptions. Mass number for Bi is (a) 209, (b) 208, (c) 207, (d) 206, (e) 205, and (f) 204.

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Preliminary Results from the Study of ^{193}Ir Level Structure by the $^{193}\text{Ir}(n,n'\gamma)$ Reaction

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Previous studies of the ^{193}Ir level structure include beta decay,¹ $(n,n'\gamma)$ reactions using a broad spectrum of epithermal neutrons from a reactor,² $(n,n'\gamma)$ reactions using nearly monoenergetic, accelerator-produced neutrons³; charged-particle reaction studies⁴⁻⁸; and Coulomb excitation.⁹ These studies provide a fairly complete picture of the ^{193}Ir nuclear structure up to about 900 keV (Fig. 1).

Because of this, our research has concentrated on establishing levels up to about 2.5 MeV by studying their gamma-ray decay. Our emphasis is on understanding, as completely as possible, the gamma-ray decay paths that lead to the 10.6-d $11/2^-$ isomer at 80 keV in ^{193}Ir .

We have undertaken the calculation of the (n,n') production cross section for the ^{193}Ir isomer by using

the statistical model formalism.¹⁰ Detailed nuclear-structure information is necessary to determine how higher-lying levels in ^{193}Ir that are populated by the (n,n') reaction decay to either the ground state or the isomer. A preliminary calculation of this cross section for a neutron energy of 8 MeV made use of limited nuclear-structure information. This calculation obtained a cross section approximately 30% lower than the one measured data point at 8 MeV. We undertook this experiment to significantly increase the amount of nuclear-structure information on ^{193}Ir that is necessary as input to such a calculation.

Experimental Procedure

The experiment was done at the Van de Graaff accelerator at the University of Kentucky, using the experimental procedure described in Ref. 3. Nearly monoenergetic neutrons were produced with the $^3\text{H}(p,n)$ reaction by using a pulsed proton beam. The scattering sample consisted of 68 g of iridium enriched to 99% in ^{193}Ir .

Gamma rays from the $(n,n'\gamma)$ reaction were detected with a well-shielded germanium detector located approximately 1.1 m from the target. Gamma-ray spectra were accumulated in coincidence and in anticoincidence with the beam pulses in order to distinguish between gamma rays that originate in the target and those that originate

Figure 1. A portion of the ^{193}Ir level scheme known prior to this work, showing the $11/2^-$, 10.6-d isomer.

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from neutron interactions with the detector and shielding, or that might be from room background. Spectra were taken at neutron energies of 1.0 MeV, from 1.5 to 2.8 MeV in steps of 0.1 MeV, and at 3.0 and 3.5 MeV.

The neutron-beam intensity was monitored using a long counter. In addition, at selected energies, an iron target was counted in-beam to obtain information on the neutron-beam intensity. The relative efficiency of the germanium detector was calibrated by using ^{152}Eu . Calculated corrections were applied to the gamma-ray intensities to account for absorption by the thick iridium target.

Data and Results

An example of the gamma-ray spectra obtained at a neutron energy of 1.7 MeV is shown in Fig. 2, where some of the important gamma rays that feed the ^{193}Ir isomer are identified. We used the LLNL program FITEK to fit the gamma-ray spectrum for each neutron-bombardment energy.

We generated excitation functions for each gamma ray. As noted in Ref. 3, the shape of the excitation function indicates the spin of the level depopulated by the gamma ray. Figure 3 shows examples of three excitation functions from this

experiment. Excitation functions for levels with spins less than $5/2$ rise rapidly and fall again at higher energies (Fig. 3a); those for spins $7/2$ and $9/2$ rise more gradually and tend to level off (Fig. 3b); and those for spins greater than $11/2$ rise steadily to the highest energies used in this work (Fig. 3c).

Generally, the spin of a level can be established to within one unit of angular momentum if the excitation function is well developed. In addition, in most cases the excitation energy of the excited level can be determined to within ± 50 keV from the excitation function.

Figure 2. The gamma-ray spectrum obtained with the $(n,n'\gamma)$ reaction on ^{193}Ir at a neutron energy of 1.7 MeV. Several of the gamma rays that populate the isomer are labeled with their energy. Gamma rays that form cascades with the labeled gamma rays are indicated by asterisks.

Figure 3. Excitation-function shapes for three gamma rays, which illustrate how shape can be used to determine the approximate spin of the decaying level. (a) The 627.3-keV excitation function indicates a low spin, probably $3/2$. (b) The 662.7-keV excitation function indicates a spin of $7/2$ or $9/2$. (c) The 503.1-keV excitation function indicates a high spin, possibly $13/2$. These shapes agree qualitatively with those obtained in Ref. 3 for similar spin levels.

More than 100 new excited states in ^{193}Ir are established on the basis of the gamma-ray energy plus level-energy sums and the threshold exhibited by the gamma-ray excitation functions. Two or more depopulating gamma rays are identified for only about 50 new levels. In these cases, the intensities of the gamma rays are approximately equal. Only in a few instances do the intensities of two or more gamma rays from a given level differ by more than a factor of 5.

Using the Ritz principle, we conducted a systematic search for new levels that included all gamma rays with thresholds below 1.9 MeV and all pairs of levels up to 0.9 MeV. Nevertheless, numerous intense gamma rays remained unplaced after that search. We conclude that a number of excited levels decay primarily by a single, intense, gamma

ray and that other possible decay branches are too weak to detect in this experiment. Thus, many excited levels were established on the basis of a single gamma ray for which the threshold can be accurately determined. In many instances, more than one final level is within the uncertainty of ± 50 keV resulting from the threshold determination. The choice of the final level is made consistent with the spin of the decaying level, as indicated by the shape of the excitation function and the assumption that transitions are dipole or electric-quadrupole in nature. In many cases, the new level energy is not uniquely determined by this procedure, although the existence of the level at about that energy and spin is clearly established.

The $11/2^-$ isomer in ^{193}Ir results from the presence of the unique-parity $h_{11/2}$ proton orbital. To

Table 1. Branching ratios (BR) for E1 transitions that could connect established negative- and positive-parity levels.^a

E_i	J_i^π	E_f	J_f^π	E_γ	BR (%)
299	$7/2^-$	139	$5/2^+$	160.3	<1.5
516	$7/2^+$	299	$7/2^-$	217.2	^b
521	$9/2^+$	80	$11/2^-$	441.6	^b
521	$9/2^+$	299	$7/2^-$	232.6	$<5^b$
559	$5/2^+$	299	$7/2^-$	260.0	<3
563	$(9/2^-)$	357	$7/2^+$	205.6	<4
598	$3/2^-$	0	$3/2^+$	598.2	^b
598	$3/2^-$	73	$1/2^+$	525.0	8.8
598	$3/2^-$	139	$5/2^+$	459.2	^b
598	$3/2^-$	180	$3/2^+$	418.1	4.5
598	$3/2^-$	362	$5/2^+$	236.3	<2
621	$7/2^+$	299	$7/2^-$	321.6	$<4^b$
694	$(5/2^+)$	299	$7/2^-$	395.6	^b
740	$(5/2^-)$	0	$3/2^+$	740.1	<1
740	$(5/2^-)$	139	$5/2^+$	601.2	<2
807	$5/2^+, 7/2^-$	299	$7/2^-$	507.6	$<9^c$
829	$(9/2^+)$	80	$11/2^-$	748.5	68
829	$(9/2^+)$	299	$7/2^-$	529.5	^b
833	$9/2^-$	358	$7/2^+$	475.5	^b
834	$(9/2^+)$	80	$11/2^-$	754.5	$<9^b$

^a Depopulating E1 transitions are clearly established only for the decay of the $3/2^-$, 598-keV level and possibly the $(9/2^+)$, 829-keV level.

^b Interference from an intense gamma ray placed elsewhere in the level scheme.

^c Interference from the 511-keV annihilation line.

determine the isomer production cross section, we must know as well as possible the E1 transitions that connect the positive and negative parity levels. The gamma-ray spectrum taken at a neutron energy of 1.7 MeV was accumulated with about three times as many events as the other spectra to ascertain the existence of E1 transitions.

Table 1 summarizes the well-established cases where upper limits are established on E1 transitions that connect levels of different parities. In several cases, potential E1 transitions coincide with strong transitions placed elsewhere in the level scheme. Only in one instance—that of the decay of the $3/2^-$, 598-keV level—are E1 transitions clearly established to compete with an E2 transition depopulating a level.³ Also, the 824-keV level—tentatively assigned ($9/2^+$)—has transitions to the $11/2^-$, 80-keV and $5/2^+$, 559-keV levels, respectively, indicating that some positive-parity, high-spin levels may decay to the $11/2^-$ level. In all other cases where there is no interference in the spectrum, upper limits of less than 5% are established for E1 branching ratios. Because of this

result, parities for new levels were assigned to be the same as that of the populated level in most instances.

Conclusion

More than 100 new excited levels are established in ^{193}Ir using the $(n,n'\gamma)$ reaction. Only upper limits can be established for E1 transitions in most cases, indicating little crossover feeding from levels of one parity to those of the other parity. These data significantly increase the experimentally determined nuclear-structure information that can be used to calculate the neutron-production cross section for $^{193}\text{Ir}^m$.

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Additional Cross-Section Computational Studies for Iridium

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Last year, we reported on preliminary calculations of cross sections for several iridium isotopes.¹ We recommended that these calculations be used only for sensitivity studies of the utilization of iridium as a radiochemical detector in device tests. Our radiochemical diagnostic

measurements involve either single isomers or, since portions of some of the cross sections end up in very long-lived isomeric states, sums of the ground state plus one or more short-lived isomeric populations. To calculate the ground- and isomeric-state populations correctly, a

complete set of reliable, discrete nuclear levels and their multipole branchings must be available for each iridium isotope.

The principal problems we encountered in our initial calculations were that the discrete-level information, as well as most of the

existing experimental reaction cross-section data, is presently incomplete and/or uncertain. On the basis of our calculations, however, we were able to point out problems in the level information, particularly for the odd-odd iridium isotopes. Much new experimental and theoretical work is now under way by members of the Nuclear Chemistry Division and others, primarily on the isotopes ^{191}Ir – ^{194}Ir .

Comparisons of Optical-Model Potentials

We have compared the results obtained when we use two available iridium optical-model potentials (OMPs) to compute neutron transmission coefficients: a potential originally deduced by Bersillon and Arthur at Bruyeres-le-Chatel (herein called the BLC OMP)² and a potential modified later by Arthur³ to yield larger total reaction cross sections for incident neutrons, E_n , above 10 MeV. The latter potential (herein called the Arthur OMP) was used in our preliminary set of iridium

cross-section calculations. Further comparison of our calculated total (n,2n) and (n,3n) cross sections on ^{191}Ir and ^{193}Ir with existing measurements indicates that, with our choices of values for the other input parameters, the BLC OMP gives a better fit than the Arthur OMP. This observation includes the use of Nagle's preliminary measured cross-section values⁴ for the production of the 241-y $^{192\text{m}}\text{Ir}$ by the $^{193}\text{Ir}(n,2n)$ reaction at around 14 MeV. The total (n,xn) cross sections computed with the Arthur OMP are about 10 to 15% higher than those computed with the BLC OMP for incident neutron energies above 10 MeV.

Evaluation of Precompound Model Improvements

The improvements we have made in the precompound exciton model in the STAPRE code are described in detail elsewhere in this report.^{5,6} To evaluate these improvements, we carried out some sensitivity studies on the calculation of the $^{191,193}\text{Ir}(n,xn)$ cross sections. We find that when the matrix element for residual interaction, $|M|^2$, is calculated on the basis of defining the level density parameter, a , for both the first and residual compound nuclei as $a = A/8$ (where A is the mass number) and using the new exciton-dependent spin-cutoff parameter, σ_p^2 , results for the total (n,2n) and (n,3n) cross sections appear to be better than those obtained with our original modeling.⁷ In the case of $^{193}\text{Ir} + n$, the magnitude of the differences obtained using the new precompound modeling vs the original precompound modeling are, for $E_n \geq 14$ MeV, about 2 to 8% for total (n,2n) and (n,3n) cross sections and about 16 to 22% for (n,n') cross sections. However, around $E_n = 9$ MeV, where precompound contributions are small, the effect was less than 1%.

In Fig. 1, we show the differences in the $^{193}\text{Ir}(n,n')^{193\text{m}}\text{Ir}$ cross sections that result from the use of the original or newly modified exciton-dependent spin-cutoff parameter. Both calculations used the BLC OMP and the same method of calculation of $|M|^2$. At $E_n = 20$ MeV, the new σ_p^2 yields only 25% of the value that the original σ_p^2 gave for the inelastic cross section to the isomer. At $E_n = 14$ MeV, the new modeling gives about one-third the value given by the original. At lower incident energies, for example, $E_n = 6$ MeV, the effect of using one or the other σ_p^2 is only about 5%. The data from Bayhurst and coworkers⁸ are not accurate enough for us to decide quantitatively whether the new modeling of σ_p^2 is an improvement over the original modeling. We must study more target elements having a wide range in mass and more extensive experimental data (such as yttrium, zirconium, lutetium, bismuth, and neptunium) to decide if the new σ_p^2 produces better results and when one of the other methods is more reliable for calculating $|M|^2$.

Analyses of the ^{192}Ir Discrete-Level Information

We have made calculations for several types of reactions to improve our understanding of the level structure in ^{192}Ir . For example, we carried out a preliminary analysis of Hoff's⁹ average resonance capture (ARC) data for 2-keV neutrons incident on ^{191}Ir . This was done using our absolute E1, M1, and E2 strength functions¹⁰ to calculate the intensities of the primary capture gamma-ray transitions to levels up to about 0.5 MeV in ^{192}Ir . The initial spin distribution produced in ^{192}Ir by the 2-keV neutrons was computed by our version of the COMNUC code¹¹ and then entered as input into the

Figure 1. Calculated cross sections vs E_n for the reaction $^{193}\text{Ir}(n,n')^{193\text{m}}\text{Ir}$ using the original spin-cutoff parameter in the precompound modeling and the newly modified exciton-dependent spin-cutoff parameter. Data from Bayhurst and coworkers⁸ are shown for comparison.

STAPRE code.⁷ The uncertainty associated with transitions to all of the final states was also calculated from the square root of the variance and found to be about $\pm 12\%$.

The results of these calculations are shown in Fig. 2 as shaded bands. By normalizing these calculations to several of the experimental transitions, we were able to make spin and parity assignments for the levels observed in the data. Our transition-intensity calculations cannot distinguish between level spins of $1^-, 2^-$ and $1^+, 2^+$. Transitions to 4^+ levels are essentially only E2 in type. The number of J^π states from 0 to 3 that we identified in Hoff's data agreed well with our prediction of last year. Although our calculations for this analysis are as complete as we can make them, the analysis and interpretation of the data are by no means

final. Our principal interest was to compose an intermediate set of ^{192}Ir levels and gamma-ray branches that was as correct as possible for use in our cross-section calculations.

As shown last year,¹ when we used the original set of 37 discrete levels for ^{192}Ir and their accompanying gamma-ray branches (as supplied by Meyer¹²) in our calculation of the cross sections for the reaction $^{193}\text{Ir}(n,2n)^{192}\text{g+m1Ir}$, we were low by a factor of about 2 compared to the data at $E_n \approx 14$ MeV (Refs. 8, 13). The incomplete level set and branching ratios caused far too much of the calculated $(n,2n)$ cross section to populate the 9^+ , 241-y isomer at 0.161 MeV. Within this last year, Paar and Brant,¹⁴ in collaboration with Meyer, calculated a preliminary set of 150 levels, using their Interacting Boson Fermion Fermion Model (IBFFM).¹⁵

Only the level energies, spins, and parities were calculated; no gamma-ray branching fractions were computed. We used the LCHECK code to calculate the missing gamma-ray branches.¹⁶ However, as seen in Fig. 3, when this theoretical level set is used in our $(n,2n)$ calculations, the improvement over use of the original 37-level set is slight. When we compared the theoretical ^{192}Ir level set with the ARC data, it was clear that the 150-level set, as well as the original 37-level set, was significantly deficient in levels with spins in the range $J = 0$ to 3. We assembled a third level set for ^{192}Ir in which we took all of the levels that we had characterized from our analysis of the ARC data, levels having spins with $J = 0$ to 3, and combined them with the IBFFM levels having $J \geq 4$, up to level energies of about

Figure 2. Our calculated primary gamma-ray relative intensities divided by E_γ^5 vs E_γ for E1, M1, and E2 transitions to final states in ^{192}Ir with spins of 0^- to 3^- and of 0^+ to 4^+ following 2-keV neutron capture by ^{191}Ir . The shaded bands arise from the calculation of a $\pm 12\%$ uncertainty associated with the computed transition intensities and based on the square root of the variance.

Figure 3. Calculated excitation functions for the total $^{193}\text{Ir}(n,2n)^{192}\text{Ir}$ reaction and for the $^{193}\text{Ir}(n,2n)$ production of the sum of the ^{192}Ir ground state and first isomer ($g + m1$) using different discrete level sets and associated gamma-ray branchings for ^{192}Ir : 37-level set of Meyer,¹² preliminary theoretical 150-level set¹⁴ with LCHECK-computed gamma-ray branches, and our deduced 73-level set. Data from Bayhurst and coworkers⁸ and Herman and coworkers¹³ for the $^{193}\text{Ir}(n,2n)^{192}\text{g+m1Ir}$ reaction are shown for comparison.

0.5 MeV. This yielded a set of 73 levels, for which we generated gamma-ray branchings using the LCHECK code. As shown in Fig. 3, this ad hoc level set reproduced the experimental $^{192g+m}\text{Ir}$ production from the $^{193}\text{Ir}(n,2n)$ reaction to within about 10%.

Reexamination of the $^{193}\text{Ir}(n,\gamma)$ Data Discrepancies

We also reexamined the 50 to 80% discrepancies exhibited among the three sets of experimental data cited last year for the $^{193}\text{Ir}(n,\gamma)$ excitation function.¹ The question of which data set is most reliable appears to be resolved by comparisons¹⁷ that we have made with the (n,γ) cross sections for elemental iridium that were

measured by Joly and coworkers.¹⁸ When we properly weight and combine the (n,γ) cross-section data for ^{191}Ir (37.3% abundant) and ^{193}Ir (62.7% abundant) that were measured by Lindner and coworkers¹⁹ via the activation method, we find very good agreement (Fig. 4) with the Joly data for natural iridium that was obtained by using a gamma-ray spectrum measurement technique.¹⁸ The natural iridium neutron-capture cross sections constructed from the data sets of Macklin and coworkers,²⁰ which were obtained from prompt gamma-ray measurements, lie below the Joly data; the constructed natural iridium cross sections from the data sets of Herman and coworkers,²¹ which were

obtained from activation measurements also, lie well above the Joly data. Our original calculations for the $^{193}\text{Ir}(n,\gamma)$ excitation function agreed with the lower data of Macklin and coworkers. We now know how we must modify the level-density modeling in ^{194}Ir to allow us to match the Lindner data. We are investigating what this modification tells us regarding the number of ^{194}Ir discrete levels that should be present up to a particular excitation energy.

Production of the 0.47-y ^{194}Ir Isomer via Neutron Capture

Finally, we have examined in more detail the production of the 11 π , 0.47-y isomer of ^{194}Ir via neutron capture on the 3/2 $^+$ ground state and on the 11/2 $^-$, 10.6-d isomer of ^{193}Ir . Our calculated results are shown in Fig. 5. The cross section for $^{193g}\text{Ir}(n,\gamma)^{194m}\text{Ir}$ is small, a few tenths of a millibarn for incident neutrons in the range of 1 keV to several MeV, and is rather flat and independent of energy. The cross section for the isomer target ^{193m}Ir has a more traditional shape, decreasing from about 500 mb at $E_n = 1$ keV to about 10 mb for E_n equal to several MeV. These results indicate that the isomer ^{194m}Ir might provide interesting new diagnostic information for nuclear tests, if it can be measured accurately. It is not produced well by neutron capture on ^{193g}Ir ; thus, it might provide supplementary information about the production and destruction of the ^{193}Ir isomer, itself produced mainly by neutron inelastic scattering from the ground state.

Figure 4. The (n,γ) cross sections for natural iridium vs E_n as reported by Joly and coworkers¹⁸ and as constructed from the reported data of Lindner and coworkers,¹⁹ Macklin and coworkers,²⁰ and Herman and coworkers.²¹

Figure 5. Our calculated excitation functions for the reactions (a) $^{193}\text{gIr}(n,\gamma)^{194}\text{g,mIr}$ and (b) $^{193}\text{mIr}(n,\gamma)^{194}\text{g,mIr}$.

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Completion and Applications of the PC Code LCHECK

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Last year,¹ we described three IBM PC codes that we were developing for use in conjunction with our cross-section calculations: LCHECK, INDIGO, and CADISE (Cross-section Analysis with Data Interpolation on a Standard Energy-grid, formerly called PC GERALDINE). Here, we discuss the completion of the LCHECK code and some of its early applications. We also summarize the status of the INDIGO and CADISE codes.

LCHECK Code Description

The LCHECK code was designed to operate in three modes:

- **Data File Error Analysis mode.** In this mode, the code analyzes the input file containing the discrete levels and their multipole branches for a number of typographical and/or physics errors. This analysis is very important to us because often our level sets are composed of hundreds of levels, each of which may have as many as 30 branches—it is virtually impossible to hand-check such large sets.
- **Interactive Data File Generation mode.** This mode allows the user to create sets of discrete levels and their associated branching ratios in the format required by the STAPRE code,² even though the user is entering the information in the (different) format usually used by our nuclear structure personnel. The results can be analyzed by the Error Analysis mode, and the user can then correct any errors.
- **Branching Ratios Calculations mode.** This mode, now completed and debugged, is described below.

The Branching Ratios Calculation Mode. In the Branching Ratios Calculations mode, the discrete level set is read and the multipole branching ratios among the levels are computed under one of two possible assumptions: (1) the levels have no collective character, or (2) the levels are all rotational band heads with the rest of each band deleted. In both cases, the energy dependence of the transitions is assumed to be $E_\gamma^{(2\ell+1)}$, where ℓ is the multipolarity. Only E1, M1, and E2 transitions in the Weisskopf single-particle approach are considered, and the strength functions are constants; either relative or absolute values may be supplied by the user or computed from the Weisskopf approximations.

In practice, we use our absolute continuum strength-function values³ at an excitation energy midway among the discrete levels if no other information, such as that from neighboring nuclei, is available. In the continuum, E1 transitions are modeled using a double-peak, energy-dependent Breit-Wigner line shape plus our systematics for the absolute intensity as a function of mass and deformation. M1 absolute strength functions are computed from a variation of the Weisskopf approximation, even though we know this does not yield a finite sum rule. The E2 absolute strength functions are calculated using our systematics for the parameters³ plus either a Lorentz or an energy-dependent Breit-Wigner single-peak line shape.³

Up to 30 branches are calculated for each parent level; 20 may be dipole transitions and the remaining

10 may be E2 transitions. From these, the 10 most intense transitions are chosen and normalized to unity, and an output file is written in the STAPRE format. Up to six levels may be specified by the user as isomers, and the code will also identify as isomers levels that cannot decay by dipole or E2 transitions. If the levels are all collective band heads, the user has the option of invoking the K-quantum number-selection rules. If so, then the K-quantum numbers must be supplied when K does not equal the spin, J , of the band head. The main use for this aspect of the third mode was to be able to insert E2 branches in level sets generated by codes having only dipole transitions.

Sample Uses of the Branching Ratios Calculation Mode. Elsewhere in this report,⁴ we illustrate the use of our new spin-dependent precompound reaction model by showing calculations of the excitation function for the reaction $^{209}\text{Bi}(n,2n)^{208\text{m}}\text{Bi}$. Using the original branching ratios supplied by Meyer⁵ for a set of 87 levels up to an energy of 2.1 MeV, we calculate the population of the 10^- isomer at 1.57 MeV to be about 14% of the total (n,2n) cross section for an incident neutron energy of about 14 MeV. That illustration also shows the results obtained using the multipole transitions computed by the LCHECK code, which are within 10% of the original results.

In Table 1, we show a portion of the branching information from the original set and from the LCHECK-generated set. When an isomer is present, the format of the STAPRE

code requires that this level be omitted from the set of branches. Level number 21 corresponds to the 10^- isomer of ^{208}Bi and was located and deleted by LCHECK. The designation of a state as an isomer depends upon the user's criterion for the magnitude of the half-life. In this case, the 10^- isomer has a half-life of 2.5 ms. Should we choose not to call this state an isomer because the half-life is too short for the application, we would simply insert one line in the branching file with our choice of final states and the fractional branches to them. Although the LCHECK branches in Table 1 repro-

duce the isomeric cross section rather well, it is obvious that each parent level has been assigned many more branches than are contained in the original set. Thus, the gamma-ray spectrum computed from each set might differ markedly.

To investigate this further, we computed the cross sections and gamma-ray emission spectra for the $^{191}\text{Ir}(n,n')^{191}\text{g,mIr}$ reaction, from threshold to 4 MeV. The isotope ^{191}Ir has a 4.9-s, $11/2^-$ isomer at 0.17 MeV; the calculated cross sections for its production are shown in Fig. 1a with a single experimental value.⁶ Again, the results from LCHECK

agree fairly well with both the measurement and the calculation using the original multipole branches.⁵ However, when the calculated gamma-ray emission spectra associated with the inelastic scattering of 2-MeV neutrons using the two branching sets (with intense transitions corrected for K_α electron conversion) were compared with new experimental measurements,⁷ neither calculation agreed well with the data. Both calculations and measurements showed one main transition along with a number of somewhat less-intense transitions, but the energy of the main transition was

Table 1. Multipole branches among the first 28 of a total of 87 discrete levels for ^{208}Bi , as computed using original branching ratios⁵ and those from LCHECK.

N_i^c	Set 1 ^a		Set 2 ^b										
	$N_f + \text{BF}_f^d$		$N_f + \text{BF}_f^d$										
2	1.00		1.000										
3	1.00		1.999	2.001									
4	1.68	2.32	1.582	2.418									
5	2.00		1.577	2.420	3.004								
6	2.00		1.006	2.994									
7	1.54	3.46	1.317	3.683									
8	1.50	2.50	1.517	2.414	3.039	4.017	5.013						
9	6.00		2.175	4.001	6.824								
10	4.30	6.70	1.011	2.902	4.050	6.037							
11	1.30	2.70	1.514	2.419	4.026	5.021	6.020						
12	1.60	2.40	1.495	2.409	4.036	5.030	6.028	8.001					
13	2.84	4.16	1.013	2.832	4.083	6.067	9.002	10.002	11.001				
14	1.00		1.763	2.007	3.115	5.059	7.050	8.005					
15	1.40	4.60	1.400	2.347	4.071	5.064	6.063	8.018	10.013	11.011	12.006	13.005	
16	4.60	10.40	1.016	2.614	4.136	6.121	9.031	10.029	11.025	12.015	13.011		
17	1.60	2.40	1.373	2.326	3.102	4.075	5.069	8.023	11.015	12.010	14.006		
18	1.20	2.80	1.016	2.566	4.141	5.001	6.128	9.039	10.037	11.033	12.022	13.017	
19	6.00		2.056	4.006	6.538	9.167	10.158	13.075					
20	2.00		1.357	2.315	4.082	5.075	6.074	8.028	10.023	11.020	12.014	13.011	
22	1.50	3.50	1.530	2.012	3.166	4.001	5.118	7.109	8.047	14.017			
23	1.00		1.525	3.170	5.122	7.114	8.050	14.019					
24	1.60	2.40	1.017	2.519	4.145	6.132	9.047	10.045	11.041	12.029	13.024	15.002	
25	7.00		7.000										
26	1.00		1.336	2.299	4.086	5.080	6.079	8.034	10.028	11.025	12.018	13.015	
27	3.00		3.555	7.377	14.068								
28	1.00		1.327	2.292	4.088	5.082	6.081	8.036	10.030	11.027	12.020	13.017	

^a Using original branching ratios.⁵

^b Branches computed by the LCHECK code.

^c N_i is the number of initial radiating level (1 = ground state, 2 = first excited state, etc.).

^d N_f is the number of the level reached by the transition, and BF_f is the fraction of all transitions from level N_i that terminate at N_f . When $\text{BF}_f = 0$, the branching fraction to level N_f is unity.

misassigned by both calculations. Our interpretation of this is that one or more important levels are missing from the present ^{191}Ir discrete level set we are using,⁵ but the number of missing levels is small enough that the (n,n') cross section to the isomer is not greatly affected. That the LCHECK code could reproduce

the isomer ratio in ^{191}Ir so well was surprising because the nucleus is away from closed shells, is deformed, and probably resembles an asymmetric rotor or vibrator more than a spherical nucleus.

Of greater importance to nuclear-test diagnostics are the cross sections for the $^{193}\text{Ir}(n,n')^{193\text{m}}\text{Ir}$ reaction that produce the 10.6-d product at 0.08 MeV. Because both ^{191}Ir and ^{193}Ir have ground-state spins of $3/2^+$ and isomers with spins of $11/2^-$, we would expect similar (n,n') excitation functions, allowing for the energy differences. It is very important that we be able to correctly calculate the $^{193}\text{Ir}(n,n')^{193\text{m}}\text{Ir}$ excitation function, as we seem to be able to do when ^{191}Ir is the target. The present situation is given in Fig. 1b. Using a set of 37 discrete levels for ^{193}Ir , neither the original multipole branches⁵ nor those from the LCHECK code can reproduce the measurements of Bayhurst and coworkers.⁸ A comparison of Fig. 1a and b suggests that the calculations for target ^{193}Ir are not grossly in error. Efforts are now under way both to remeasure this reaction⁹ and to calculate the levels and their branches using an approach similar to the Interacting Boson Approximation.¹⁰ We cannot conceive of any cross-section modifications (except an extremely unlikely level set and branches) that could possibly reproduce the data point near $E_n = 7$ MeV. Again, reasonable (and unexpectedly good) agreement is obtained when either the original or LCHECK branches are used.

One of the most interesting applications of the LCHECK-computed branchings was for ^{192}Ir in the calculation of the cross section for the $^{193}\text{Ir}(n,2n)^{192\text{m}}\text{Ir}$ reaction. Here m2 refers to the 9^+ , 241-y isomer at an energy of 0.16 MeV. This odd-odd nucleus is very difficult to study

experimentally or to describe well in theoretical calculations. Details of our cross-section calculations for this case are given elsewhere in this report.¹¹ A more well-behaved odd-odd nucleus is ^{210}Bi . Experimental cross-section data for the ^{209}Bi neutron capture reaction to the 3×10^6 y isomeric state of ^{210}Bi at 0.27 MeV do not exist, other than at thermal energy. We have made the calculations,^{12,13} using 29 discrete levels in ^{210}Bi and both the original set of multipole branches⁵ and that calculated with LCHECK, and we arrived at the excitation functions shown in Fig. 1c. The two calculations agree to within about 20%, even when the isomer fraction is so small.

Plans for the Third Mode. The Branching Ratios Calculations mode of the PC LCHECK code appears to reproduce multipole branches for sets of discrete levels using simple physics approximations that are useful even for nuclei not directly on closed shells. We intend to test this mode next on permanent rotors such as $^{174,176}\text{Lu}$ and $^{236,237}\text{Np}$. Should we continue to observe good results, we will have a valuable tool because, in many instances, it is easier, experimentally and theoretically, to determine a reasonably accurate set of discrete nuclear levels than it is to arrive at the multipole branches among the levels. Furthermore, comparing calculated transition strengths with experiment may provide information about the completeness of the level sets (as in the ^{191}Ir inelastic-scattering results mentioned above) and, thus, may supplement our statistical analyses of these level sets (spin and parity distributions, spin-cutoff parameters, density of levels, etc.).

Accurate and extensive discrete-level sets and their branches are extremely important for calculating nuclear-reaction cross sections in the

Figure 1. Measured and calculated values of isomer production from two sets of calculations—those calculated using the original branching ratios supplied by Meyer⁵ and those using the Branching Ratios Calculations mode of the LCHECK code. (a) The $11/2^-$ isomer of ^{191}Ir via the $^{191}\text{Ir}(n,n')$ reaction; (b) the $11/2^-$ isomer of ^{193}Ir via the $^{193}\text{Ir}(n,n')$ reaction; (c) the 9^- isomer of ^{210}Bi via the $^{209}\text{Bi}(n,\gamma)$ reaction. The “totals” shown in (a) and (c) are the calculated excitation functions for the total $^{191}\text{Ir}(n,n')$ and $^{209}\text{Bi}(n,\gamma)$ reactions, respectively.

energy region of interest for radiochemical diagnostics of nuclear tests, and they are indispensable if isomer populations are required. Anything that we can do to increase our confidence in these level sets should be investigated.

Progress on INDIGO and CADISE

The planned addition of one more option to the graphics code INDIGO should enable easier comparison of calculated excitation functions with experimental data that were measured under conditions of poor incident-particle energy resolution. The calculated excitation functions may be "smeared" by folding them against a unit Gaussian function with an energy-dependent width. The form of the resolution width will be

$$R = a(E - b)^2 + c(E - b) + d \quad (1)$$

Any of the constants a , b , c , or d may be negative in sign, and those not supplied by the user will be assumed to be zero. As we have shown,¹⁴ for example, when the cross section for the $^{209}\text{Bi}(n,3n)^{207}\text{Bi}$ is measured with neutrons having an energy spread from 14.1 to 15.5 MeV from a 400-keV(d,t) neutron source at zero degrees, the convolution of the rapidly rising calculated excitation function with the expected neutron distribution function produces a measured cross-section value about twice as large as the calculated one, at a nominal neutron energy of about 14.9 MeV. Similar situations arise at incident energies near rapidly rising or falling regions of cross-section excitation functions, whenever the energy resolution of the incident particles cannot be neglected.

The CADISE code was designed as a graphical preprocessing code that compiles and prepares calculated cross-section excitation functions for energy-group averaging and for further use in other codes that make activation calculations for radiochemical device diagnostics. This code has been completed, and a user's guide has been written.¹⁵ We have also modified STAPRE, our main Hauser-Feshbach plus precompound-evaporation nuclear-reaction code, to produce an output file containing all of the cross sections (total and partials to the product's ground and isomeric states) that are required by CADISE.

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A Simplified Spin-Dependent Exciton Model

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Until recently, no formalism of the precompound-evaporation nuclear-reaction model properly conserved angular momentum and parity. Most nuclear reaction codes in routine use treat the precompound and the compound portions of a given reaction separately; they do not conserve spin or parity in the precompound evaporation and often do not attempt to have the physics parameters of the precompound model approach those of the compound model as the nucleus approaches equilibrium.¹ Fu^{2,3} and a number of other investigators⁴⁻⁹ had proposed attempts at unifying the precompound and compound (Hauser-Feshbach) components of nuclear reactions; however, there always appeared to be adjustable parameters needing determination in some ad hoc manner. Recently, in their excellent summary of the current situation, Akkermans and Gruppelaar¹⁰ cite two papers^{11,12} in which the authors report successfully combining both reaction mechanisms while conserving angular momentum and parity throughout the entire process. The master-equation, exciton model¹³ was the basis of these approaches.

Although a unified reaction theory is clearly desirable from many viewpoints, for most applications in the past, the simple addition of Hauser-Feshbach compound-nucleus results with those from one of several precompound models lacking spin and parity conservation has actually produced quite adequate results.¹ Where the spin dependence of the precompound portion becomes important is in the calculation of angular distributions

and angle-integrated cross sections to isomeric states, the latter being particularly important in our present cross-section calculational effort for the iridium detector.¹⁴

On the basis of initial sensitivity studies with our iridium and bismuth cross-section libraries, we observed that under certain conditions involving type of reaction, energy of the incident particles, spins of the target and daughter nuclei, and the mass region of the target, the original exciton model¹³ in our version of the STAPRE code¹⁵ may produce isomer ratios that differ by several tens of percent or more when compared with results obtained if spin dependence in the precompound model is considered. To have in operation, in a short time, a code that still contains the many other modifications we have added over the years to the original STAPRE version, we decided to attempt an ad hoc inclusion of spin dependence in our current precompound model rather than go to a unified model at this time.

Modifications to the Exciton Model

The STAPRE code divides the excitation-energy range of interest, which is based on the energy of the incident particle and its separation energy from the first compound nucleus, into energy bins of almost any desired size. The precompound fraction and energy spectrum are computed in the master-equation, exciton framework.¹³ Originally, the precompound contribution to each energy bin in the daughter nucleus was distributed over the spin and parity states in that bin exactly as in

the Hauser-Feshbach, compound-nucleus case. Finally, the partial widths for particle and gamma-ray emission from each initial (J, π, E) state to each final (J', π', E') state, calculated for the compound-nucleus case, are used to decay the sum of both the compound and precompound occupations of the initial states in the first daughter nucleus.

We have completed the first phase of our planned modification: the change in the way the precompound spectrum is distributed over the J^π states in each energy bin in the first daughter nucleus. We did this by using an approach based on the previous work of Fu,^{2,3} Reffo,^{5,6} and Feshbach,⁹ where the spin distribution of the level density in the continuum is made dependent on the number of particles and holes in each exciton state that undergoes particle evaporation. In addition, we have made this spin distribution dependent not only on particle-hole number but also on the excitation energy in the daughter nucleus. Thus, the spin distribution and the precompound occupations approach those of the compound case at all energies as the particle-hole number increases.

We treat this problem through the use of an exciton-dependent, spin-cutoff parameter, which we have made energy dependent as well. For a given exciton state with N_p and $N_h = N$ particles and holes, the spin-cutoff parameter is taken as $\sigma_p^2(N) = \text{const}(NA^{2/3})$. Others have sometimes made a further simplification such that $\sigma_p^2(N)$ is used for all exciton states, where N is the most probable configuration. The value of the constant is in the range of 0.15 to 0.30. The usual assumption is

that the level-density expression can be factored into the product of three terms: $\rho(\pi, J, E) = F(\pi) \times F(J, E) \times \rho(E)$. The spin distribution in the precompound case, $F_p(J, N)$, would be

$$F_p(J, N) = \frac{2J+1}{2\sigma_p^2(N)} \times \exp \left[\frac{-(J+1/2)^2}{2\sigma_p^2(N)} \right] \quad (1)$$

This approach is weakly energy dependent because, at higher excitation energies, more steps are required to reach equilibrium, and particle evaporation occurs from more exciton states.

In STAPRE, the algorithm for computing the number of exciton configurations required to "sufficiently" approach equilibrium is $n_{eq} \approx (2gE_X)^{1/2}$, where g is the state density at the Fermi level and is related to the Fermi gas-level-density parameter, a , by the expression $g = (6/\pi^2)a$, and E_X is the excitation energy in the evaporating nucleus. It is easy to show that $(2gE_X)^{1/2} \approx (aE)^{1/2}$. Therefore, if we take N_C , the number of particles and holes in the last exciton configuration, as $N_C = 2n_{eq}$, then:

$$\sigma_p^2(N_C, E) = CA^{2/3}(aE)^{1/2} \quad (2)$$

Here, E refers to the excitation energy in the daughter nucleus. The spin-cutoff parameter for the compound nucleus is calculated from $\sigma_C^2(E) = (6/\pi^2)kA^{2/3}(aE)^{1/2}$, with values of k usually in the range of 0.146 to 0.24. This leads to the approximation:

$$\sigma_p^2(N, E) \approx \frac{N}{N_C} \sigma_C^2(E) \quad (3)$$

where N_C is more accurately calculated as $N_C = 2 \times (n_{eq} - 1) + N_1$,

with N_1 being the number of particles and holes in the first exciton configuration.

As an illustration, if the initial excitation is a $2p1h$ state and it takes ten configurations to approach equilibrium, then $\sigma_p^2(3, E) = (3/21)\sigma_C^2(E)$. The precompound evaporation to the daughter energy bin about energy E is then distributed over the spin states calculated from Eq. (1) using the compound spin-cutoff parameter, calculated at excitation energy, E , reduced by a factor of $(3/21)$. The next precompound component would be distributed using $\sigma_C^2(E) \times (5/21)$, etc.

Thus, the precompound evaporation from the first several exciton states tends to populate the lower spin values, with each successive exciton configuration populating a broader spin range as equilibrium is approached. We see this in Fig. 1, which gives the populations of the 73 discrete levels in ^{193}Ir following inelastic scattering induced by 14-MeV neutrons and after the gamma-ray cascade from the continuum is summed over both parities for each value of the level spin, J . When the discrete levels themselves depopulate via multipole transitions, the lower-spin final states will tend to be favored somewhat.

In addition, we now allow the state density parameters to be supplied as input parameters and also allow the choice of two ways in which to calculate the matrix element, $|M^2|$, for the residual interaction. Details on this modification are given elsewhere in this *Annual Report*.¹⁶

Model Testing

We have begun testing the accuracy of the present stage of our modified precompound model, primarily on isotopes of iridium and bismuth. Other mass ranges must be surveyed

before the general usefulness of the model can be ascertained. The results of some of our calculations compared with various iridium measurements appear elsewhere in this *Annual Report*.¹⁴ Here, we will only comment that, because of the effect illustrated in Fig. 1, the population of ^{193}Ir , the $11/2^-$ isomer, by incident 14-MeV neutrons on the $3/2^+$ ground state is lower by a factor of 3 using the new precompound model compared to that computed with the original model.

To evaluate results of our modification to reactions on ^{209}Bi , we have compared our calculations with measurements for the angle-integrated energy spectrum of emitted neutrons induced by incident neutrons of several energies, from 7 to 25.7 MeV. For $E_n = 7$ MeV, results of $d\sigma/dE_n$ vs E_n compare very well with the data of Wang and coworkers.¹⁷ However, at this energy, the precompound fraction is only about 13%, so the good agreement does not reflect much about the precompound model. At $E_n = 14$ MeV, the

Figure 1. The populations of the 73 discrete levels in ^{193}Ir resulting from use of new and old precompound models. These are the populations following inelastic scattering induced by 14-MeV neutrons and the gamma-ray cascade from the continuum, and summed over both parities for each value of the level spin, J .

precompound fraction is about 41%, and again, we find satisfactory agreement between calculation and experiment,¹⁸⁻²⁰ as illustrated in Fig. 2. The calculation used 96 discrete levels in ^{209}Bi , up to an energy of 4.8 MeV.²¹ Thus, neutrons with energies above about 9 MeV that are emitted from the precompound process populate these discrete levels along with those from direct reactions—the latter would require being described by the distorted-wave Born approximation (DWBA) formalism.

We do not expect that implementation of the second phase of our modeling will alter the shape of the precompound spectrum, shown by the blue line. However, the (n,n') and $(n,2n)$ cross sections and their spectra

of emitted neutrons may change, we hope, dropping the calculated total neutron emission in the 2- to 9-MeV region. At an incident neutron energy of 25.7 MeV, the precompound fraction is about 85%. As shown elsewhere in this *Annual Report*,¹⁶ we obtain a good fit to the data, taken between 9 and 25 MeV, with both the new and the original precompound modeling. Because there is little difference in the calculated spectra from either precompound model, we cannot conclude on the basis of these measurements that one is better than the other.

For incident neutron energies of 20 MeV or less, the effect on the total (n,n') , $(n,2n)$, and $(n,3n)$ cross sections produced by our change in the precompound model is generally

small, usually a few percent or so. A few exceptions have been observed; for example, for $^{209}\text{Bi}(n,3n)^{207}\text{Bi}$ (where the calculation populates primarily the discrete levels in ^{207}Bi), a 10% enhancement by the new model was observed for $E_n = 15$ to 21 MeV. When the $19/2^-$ isomer of ^{209}Bi is the target state, the ratio of the cross sections obtained from the original modeling to that from the new, $\sigma(\text{original})/\sigma(\text{new})$, for the $(n,2n)$ and $(n,3n)$ reactions varied from 0.5 to 1.2 for $E_n = 6$ to 21 MeV.

For our purposes, the important feature of the new modeling is its effect on isomer ratios. One way to illustrate the magnitude of the effect is shown in Fig. 3. With the ^{209}Bi ground state as target, the fractions of the (n,n') , $(n,2n)$ and $(n,3n)$ cross sections that lead to the ground states of ^{209}Bi , ^{208}Bi , and ^{207}Bi , respectively, are plotted vs E_n . For both ^{207}Bi and ^{208}Bi , the ground states have lower spin values than their isomeric states and are populated more with the new modeling. When either the $1/2^+$ or the $19/2^-$ isomeric state of ^{209}Bi is the target state, even larger differences are produced by the original and new modeling.

Figure 2. Calculated and measured total neutron emission spectra following 14-MeV neutrons incident on ^{209}Bi .

Figure 3. For the target, ^{209}Bi , the fractions of the (n,n') , $(n,2n)$, and $(n,3n)$ cross sections that lead to the ground states of the daughter products, ^{209}Bi , ^{208}Bi , and ^{207}Bi , respectively, vs E_n .

In Fig. 4, we show our calculated results for the production of the ^{208}Bi 2.5-ms, 10^- isomer at 1.57 MeV by an (n,2n) reaction on ^{209}Bi , compared with some measurements²²⁻²⁶ around 14 MeV. Figure 4 has four curves, all calculated using 89 discrete levels for ^{208}Bi . The black solid and dashed curves are those calculated using the gamma-ray branches for the 89 levels supplied by Meyer.²¹ The blue curves show the results obtained using our LCHECK PC code to compute the branches. Comparison with experiment tends to support our new precompound model. Figure 4 also illustrates the usefulness of the LCHECK code, described in detail elsewhere in this *Annual Report*.²⁷ All of our bismuth calculations shown in these figures were made using parameters determined several years ago and were not fitted to any of the measurements with which they are now compared.

Future Work

In the remaining phase of our modeling, which we plan to complete in FY 1990, we will modify the partial widths for photon emission in the daughter nucleus for each (J, π, E) state within all continuum energy bins so that they will be calculated for each subsequent precompound evaporation to conform with $\sigma_p^2(N, E)$. Then each exciton state will populate the daughter states that will undergo a gamma-ray cascade down to the discrete levels before the next exciton-state evaporation occurs. As before, each subsequent evaporation and cascade will approach the equilibrium, and spin and parity will be conserved during the cascade.

Figure 4. Calculated and measured production of ^{208m}Bi via the $^{209}\text{Bi}(n,2n)$ reaction vs E_{in} , resulting from use of new and old precompound models.

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Ruthenium as a Charged-Particle Detector for Nuclear Test Diagnostics

R. G. Lanier, M. G. Mustafa, and H. I. West, Jr.

Although the Nuclear Chemistry Division has developed and currently uses a large suite of nuclides as radiochemical tracers and particle-fluence detectors for nuclear tests, it seems prudent to continue to investigate other potential candidates for radiochemical detectors. For device-loaded, charged-particle detectors, this is particularly true for several reasons.

First, a data base of accurate charged-particle cross-section information can be developed that takes advantage of our ability to make detailed measurements of excitation functions. We have developed a target-making capability¹ that, in principle, allows us to conduct, in the laboratory, excellent charged-particle activation studies of most chemically stable materials that might be loaded into a device. Thus, accurate determinations of relevant cross sections are now limited only by the measurement technology that determines the

number of atoms created by an experiment, not by the quality of the targets. This is approximately the same limitation one encounters for determining the activation in a device. In special cases where laboratory activation cannot be accurately measured, normalizations to theoretical calculations can be done with a great deal of confidence.

Second, the development of new charged-particle detectors offers the potential for more versatility in measuring mix phenomena or for diagnosing independent segments of a device fuel more thoroughly. Additionally, having a larger variety of detectors increases the flexibility in how a detector may be loaded. For example, while halogen salts may be good candidates for mixing with salt fuels, the halogens, as non-metals, alloy with virtually nothing. Consequently, any present or future applications of such detectors in an alloy form is virtually impossible.

Finally, although the information provided by a new detector may be redundant, there is always the potential that such information may be used in a special way to probe deeper into the workings of a nuclear device.

Ruthenium as a Tracer

One of the more attractive features of ruthenium as a charged-particle detector is its relatively low reaction threshold. For protons, $E_{th} \approx 3$ MeV, and among the currently used detectors, only bromine has a more favorable proton threshold ($E_{th} \approx 2.7$ MeV). The corresponding deuterium (d) and tritium (t) thresholds with respect to protons are, of course, higher for all nuclei; however, the proton thresholds provide a base for comparing relative values. A low threshold means that the detector is able to sample a greater fraction of the charged-particle energy spectrum produced in a

device. In Fig. 1, we compare the proton excitation functions corrected for isotopic abundances for various radiochemical detectors. The ruthenium cross sections were calculated with the STAPRE code using global parameters, while those for the other nuclides were either obtained from direct measurement or from a recent evaluation.² The cross-section comparison clearly shows that ruthenium is very competitive with the other detectors being used. Although we have not compared d- and t-excitation functions, we expect that ruthenium will be competitive for these reactions also.

In Table 1, we show the rhodium activation products from the various stable isotopes of ruthenium that are expected in nuclear test debris. Because charged-particle activation is generally much weaker than activation by neutrons, interferences from fission products or from soil activation by neutrons are not necessarily negligible. However, the degree of neutron activation of naturally occurring rhodium from the $^{103}\text{Rh}(n,2n)^{102}\text{Rh}$ reaction, for example, should be negligible because rhodium's average abundance in the earth's crust is ≤ 0.001 ppm. This value is almost five orders of magnitude lower than the natural abundance of gadolinium, which is a charged-particle activation product from europium. Thus, if charged-particle activation of europium is not significantly perturbed by a natural gadolinium background, we would also expect ruthenium to be unaffected by an $(n,2n)$ interference mechanism. Since the rhodium activities (see Table 1) are neutron deficient or otherwise shielded from isobaric decay of fission products, only the direct yield from fission presents a potential interference source. This yield, however,

depends on the fission fuel used. Although such yields are expected to be very small in most cases, reasonable corrections for them can probably be determined from an evaluation of the fission performance of the nuclear device. A background problem will be present from ^{105}Rh ($t_{1/2} = 35.5$ h). The cumulative yield of this isotope is expected to be significant, and the spectrum of gamma rays will contain several lines that can interfere with an accurate determination of the other rhodium activities at short times after irradiation.

Chemically, ruthenium is a member of the platinum metal group and has several metallurgical applications. For example, it is often alloyed with platinum and palladium to form hardened alloys for wear-resistant electrical contacts. The addition of 0.1 wt% ruthenium to titanium forms a highly corrosion-resistant titanium alloy. Also, certain ruthenium-molybdenum alloys have been prepared that are believed to have superconducting properties. With respect to potential diagnostic applications, ruthenium can be alloyed with gold and

Figure 1. Proton excitation functions for yttrium, titanium, chromium, bromine, ruthenium, iodine, and europium, corrected for isotopic abundance. For comparison, the representative shape of the proton spectrum (ϕ_p) in a nuclear device is also shown.

probably with tungsten at low concentrations (<5 wt%). Phase-diagram data further suggest that additional alloys at approximately the <5-wt% level probably can be achieved with uranium and plutonium. Also, the metal can be plated on various substrates by electro-deposition or by thermal-deposition techniques. Data for simple salts or oxides of ruthenium

Table 1. Activation products of interest from a device spectrum of charged particles interacting with natural ruthenium. The natural isotopic abundances for ruthenium are also noted.

	Reaction product	Half-life
Ru + (p,d,t) $\Rightarrow$	^{102}Rh	3 y, 207 d
	^{101}Rh	3 y, 4.47 d
	^{99}Rh	15 d
Mass number	Abundance (%)	
96	5.5	
98	1.9	
99	12.7	
100	12.6	
101	17.1	
102	31.6	
104	18.6	

are scarce. However, RuO_2 is a reasonably attractive compound for mixing with salt fuels, although it has marginal stability, decomposing in the range of 500 to 700°C. Finally, the pure metal is both hard and brittle, and there appears to be no recorded experience of machining or otherwise mechanically working it. Thus, it appears unlikely that nuclear-device components could be manufactured easily from metallic ruthenium.

Discussion

Although ruthenium offers several positive features as an additional charged-particle detector, its use also presents two disadvantages. First, the determination of an absolute rhodium yield would require a volatility correction that could be quite large. This could be a serious source of uncertainty unless only the relative yields of the various isotopes or isomers are of interest. Second, if one uses ruthenium as a charged-particle detector, then there will be an interference problem if rhodium is also loaded as an (n,2n) detector. This is because some of the ruthenium charged-particle activation products would contaminate

those produced from the activation of rhodium by neutrons. We note, however, that the production of ^{99}Rh would be caused only by charged-particle activation. Thus, in principle, reasonable information on multiple neutron activation of rhodium and on charged-particle activation of ruthenium might still be obtained if ruthenium-loaded, charged-particle activation corrections could be made for $^{101,102}\text{Rh}$. Nevertheless, despite these problems, it would be interesting to observe the activation of ruthenium in a test shot and to compare its performance with well established detectors.

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Plastic-Matrix-Encapsulated Targets for Use in Measuring Nuclear Excitation Functions

H. I. West, Jr., R. M. Nuckolls, and R. G. Lanier

The general problem of selecting a suitable target for stacked-foil activation experiments involves several factors. Once the element to be studied has been selected, it is important that the target foil contain sufficient material to yield activated species with a measurable level of radiation, that the target material be homogeneously distributed throughout the foil, and that none of the activated species be lost during or after irradiation. It is also desirable that such foils have good heat conductivity and/or that the heat produced in the foil does not destroy it. If the activation product has a low cross section or a low specific activity, then the irradiation times may be long if the rate of removal of heat from the target is poor. This becomes a serious concern when cross-section measurements are attempted near the reaction threshold. Finally, a target foil should be reasonably easy to handle and should be thin enough so that beam energy loss through the foil is minimal.

Generally, single metal foils make ideal targets for activation experiments. Often, however, experiments cannot be conducted with such ideal materials, and alternate techniques have been developed to fabricate targets from metal oxides or from other chemical compounds. In our program, we were confronted with the problem of making targets that would contain europium, bromine, and iodine. Metallic europium rapidly oxidizes in air and bursts into flame at relatively low temperatures (150 to 180°C). The halogens, bromine and iodine, have physical

properties at room temperature that make them completely unsuitable for fabrication into freestanding target foils. Moreover, the (p,n) and (d,2n) activation products of both are noble gases (krypton and xenon). As a result, any target made from halogens must be specially protected to avoid losing those gaseous activation products.

Method of Making Targets

To solve the problem of making targets loaded with europium, bromine, or iodine, we developed a method of suspending suitable compounds of these materials in a plastic matrix. This technique offers a significant advantage over vacuum evaporation or sputtering, which have been used in the past, because both the target thickness and the homogeneous distribution of the material throughout the target can be readily controlled. It is also more advantageous than forming "pellets" or other self-supporting forms by mechanical compression because these tend to be rather thick constructions and are often brittle. Finally, the technique is particularly attractive because, in principle, it can be used with any material that has good chemical stability.

Not all plastics are suitable for target preparation. For example, Mylar, a polyester, breaks down in seconds under the kinds and intensities of irradiation we use. We decided to try a polyimide resin that, when polymerized, is essentially the same as Kapton, which is marketed in sheets. Kapton, we knew, was also used for scattering-chamber windows and in many other nuclear

applications, so there was already a history of its use in radiation environments. Our efforts to make foils with this resin have been quite successful. The resin contains only hydrogen, carbon, and nitrogen, and these elements have acceptable background activities when irradiated with light, charged particles.

We first tried TiO_2 for target loading. When this proved successful, we used the same procedure to make a large number of foils loaded with Eu_2O_3 . First, we thoroughly mixed finely powdered Eu_2O_3 with the resin in a paint mill. Next, we spread the mixture thinly over a clean, level, Pyrex glass surface with an area of 10×20 cm and cured it in an oven for several hours, increasing the temperature during that time to 260°C. After it was cured, the oxide-resin mixture formed a thin sheet that was fairly tough and easy to handle. From these sheets, we punched 25.4-mm-diam target foils that had total areal densities of 15 to 20 mg/cm², one-third of which was elemental europium.

For fabricating halogen targets, we have so far applied our technique only to iodine because there is already a commercially available epoxy polymer that contains bromine as part of its chemical composition. The bromine weight fraction is reasonable, and the remaining elemental components resemble the composition of Kapton. Test foils of epoxy-bromine for our evaluation were coated with aluminum to a density of 0.2 mg/cm² on both sides to contain the krypton produced during irradiation and to help in heat removal.

With a procedure similar to the one used to load targets with Eu_2O_3 , we used KI to make iodine targets. With KI, we have made reasonable foils with a total areal density of 15 to 20 mg/cm^2 with a 30% concentration of iodine. We encountered problems because KI is a coarse-grained, ionic salt and because the activation product is xenon gas. Because thorough mixing with the resin is essential for producing homogeneous films, the particle size of the solid oxide or salt must be as small as possible. Thus, before adding the resin, we thoroughly ground and sieved the salt to reduce the particle size. In addition, KI is soluble in water. Because water is a by-product of the curing process, I^- ions are probably present during polymerization. This could conceivably cause the formation of less-complete polymer chains and explain why, with KI, we produced a rubbery plastic sheet. Finally, to contain the gaseous xenon, we evaporated 0.2 mg/cm^2 of aluminum on both sides of each target foil.

Foil Calibration

It is necessary to accurately determine the areal density of the target element loaded into each of the plastic foils, preferably by a nondestructive, easily applied, and highly accurate method. The method we finally developed makes use of x-ray fluorescence analysis (spectrometry) and is based on the fact that the number of fluorescent x rays (K_α and K_β) produced in a foil is proportional to both the strength of the excitor gamma-ray source and the total amount of elements to be analyzed. By using the appropriate self-absorption coefficients, we can correct for the absorption of both the excitor gamma rays and the emitted x rays.

The count in the fluorescent x-ray peak generated by an element E can be written as:

$$C = k \mu_\gamma^E \rho z^E \Omega \left(\frac{1 - e^{-D}}{D} \right), \quad (1)$$

where

- k = calibration constant, in min^{-1} ;
- μ_γ^E = the absorption coefficient for the excitor gamma rays in element E ;
- ρz^E = areal density of element E , in mg/cm^2 ;
- Ω = solid angle the gamma-ray source subtends at the foil, which can be written as the foil area, A , divided by the average source-to-foil distance squared (i.e., $\Omega = A/r_0^2$);
- $(1 - e^{-D})/D$ = the self-absorption coefficient;
- $D = \Sigma_\gamma \mu \rho z / \cos \theta + \Sigma_x \mu \rho z$.

The first term in D is the attenuation term for gamma-ray absorption summed over all elements, and the second is for x-ray absorption summed over all elements. $\cos \theta$ is the obliquity factor for gamma-ray penetration. The obliquity factor for x rays is close to 1.00 and is not included explicitly.

For analyzing europium, iodine, and bromine, we used the 60-keV gamma rays from ^{241}Am to excite the x rays. The requirement is that the energy of the excitor gamma radiation be above the K edge of the element to be analyzed, but not by too much. We have also conducted experiments using foils loaded with TiC_2 , and here, we used the 22-keV x rays in the decay of ^{109}Cd . The term we want from the equation is ρz^E . For europium, we took advantage of the fact that, thermally, Eu_2O_3 is very stable. Thus, after a large

group of foils had been carefully compared, ten individual foils were burned to ash, and the ash was weighed as Eu_2O_3 . The k values produced were consistent to 0.5%. (In the final analysis, a calibration constant, $k\mu^E\Omega$, is used.)

For iodine, we had planned to use AgI instead of KI and to use pure silver foils to calibrate the spectrometer. Unfortunately, we found that the energies of the x rays emitted by the iodine were just above the K-absorption edge for silver, and even though the foils were thin, an appreciable amount of the iodine x rays was absorbed in the foils, thus enhancing the K x-ray peak for silver in the fluorescent spectrum. We could calculate the effect, and a code was written to do so, but the precision of the method was inadequate for our needs. Fortunately, we have found that the evaporation rate of KI at temperatures needed to burn off hydrocarbons (when burning foils to ash) is not so high as to preclude using the same procedure we used for europium. So far, we have not studied methods to determine the calibration constant for bromine.

In addition to determining the areal density of an element of interest in a foil, we need to know how uniformly distributed it is in the foil. Note that the amount of material fluoresced is $\rho z^E A$, in mg. Although the foils are 25.4 mm in diameter, a mask 15.9 mm in diameter was used to define the measured portion of the foil (A). If the charged-particle beam covers exactly the same region with a uniform scan, there is no further concern about foil uniformity. However, the beam scan in one set of experiments was square (i.e., 8×8 mm), whereas in others, it was round (10 mm in diameter). Thus, although the beam scan helps

average out severe inhomogeneities in the foils, we still have to determine elemental uniformity in our foils. Our criterion was that fluorescent counts through the 15.9-mm mask, offset from center by 8 mm and taken at three different positions, should not differ by more than 2%.

Target Use and Evaluation

We fabricated and calibrated more than 100 foils loaded with Eu_2O_3 and used them to study proton- and deuteron-induced activation at Bruyeres-le-Chatel, France, and at the Crocker Nuclear Laboratory at the University of California at Davis. Results of this work are reported elsewhere.^{1,2} Some of the foils underwent irradiation as high as 10,000 μCi over a period of up to 5 h without showing any evidence of damage that would impair their usefulness. Heat removal was facilitated by means of thin aluminum foils (areal density $> 6 \text{ mg/cm}^2$) pressed against the plastic foils. Of course, the aluminum foils served the additional purposes of recoil-ion catchers and beam-energy degraders. In addition, the beam was rastered over a foil $8 \times 8 \text{ mm}$ square to help reduce the effects of beam loading and inhomogeneities across the target.

In our first experiments with the KI-loaded foils, we found that the thin 0.2-mg/cm^2 aluminum coatings on the foils, as well as additional aluminum foils, helped in heat removal. Although the targets performed well in general, we found that there was a heat problem even

though we were careful to raster the beam (in this case, over an area 10 mm in diameter). If the heat produced in a foil is greater than about 0.5 W, the aluminum cladding can separate from the target foil, and in such cases, there is concern about loss of ^{127}Xe . We are examining the details of the foil mountings to see if we can improve heat removal.

In our preliminary tests of the epoxy-bromine foils, we found a serious heat-loading problem. In contrast to the Kapton-like foils, which were cured at 260°C , this epoxy was cured at only about 80°C . It appears that if we want to use these foils, we must keep the heat produced in the foils below about 0.2 W/foil.

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Proton and Deuteron Excitation Functions for ^{151}Eu and ^{153}Eu

H. I. West, Jr., R. G. Lanier, M. G. Mustafa, R. M. Nuckolls, J. Frehaut,* A. Adam,* and C. A. Philis*

We have used the stacked-foil method for obtaining the proton and deuteron nuclear-reaction excitation functions for $^{151,153}\text{Eu}$. The target preparation was quite important to this work. To hold our target material, Eu_2O_3 , we used a polyimide resin that polymerizes to a plastic called Kapton and is quite resistant to radiation damage, holding up well after a $1\text{-}\mu\text{A}\cdot\text{h}$ irradiation by deuterons. A detailed account covering fabrication and calibration is given elsewhere in this *Annual Report*.¹ An early account of our work for $<12\text{-MeV}$ data acquired in France was presented in last year's *Annual Report*.² Since then, we have acquired data for projectile energies of 20 to 35 MeV, using the Crocker Nuclear Laboratory (CNL) cyclotron at the University of California at

Davis. We are still in the process of accurately establishing the energies of the particles from the CNL cyclotron. As a help in this respect, complementary data at 12 to 20 MeV are being obtained following the FY 1990 upgrade of the LLNL Van de Graaff.

Results

We made most of our measurements at energies less than 12 MeV for the $^{151,153}\text{Eu}(p,n)^{151,153}\text{Gd}$ and $^{151,153}\text{Eu}(d,2n)^{151,153}\text{Gd}$ reactions at Centre d'Etudes de Bruyeres-le-Chatel (CEB), France, in June 1988. We added a few complementary points a few months later, using the LLNL Van de Graaff. (The LLNL Van de Graaff would go to only 8 MeV at that time.) To ensure that the radiation counters at both laboratories were equally well calibrated, we also counted at LLNL the samples that we had previously irradiated and counted in France. In most cases, the results compare within experimental error. Figures 1

through 4 show results for the reactions leading to the production of $^{151,153}\text{Gd}$, including both the CEB and CNL data. We note that, although the lowest projectile energy used at CNL was 20 MeV, we have data extending down to about 14 MeV as a result of the energy loss of the projectiles in the foil stacks.

In Fig. 1, we show data for both the $^{151}\text{Eu}(p,n)^{151}\text{Gd}$ and $^{153}\text{Eu}(p,3n)^{151}\text{Gd}$ reactions. To remove the (p,n) contribution to the ^{151}Gd data in the region of overlap, we normalized the high-energy tail in Fig. 1 to the $^{153}\text{Eu}(p,n)^{153}\text{Gd}$ data of Fig. 2. We have included this normalization as part of the ^{151}Gd data in Fig. 1. Figure 3 shows results for the $^{151}\text{Eu}(d,2n)^{153}\text{Gd}$ and the $^{153}\text{Eu}(d,4n)^{151}\text{Gd}$ reactions. Here, in a procedure similar to that used in Fig. 1, we have extended the high-energy tail of the $^{151}\text{Eu}(d,2n)^{151}\text{Gd}$ data by normalizing to the $^{153}\text{Eu}(d,2n)^{153}\text{Gd}$ data of Fig. 4.

In Figs. 5 and 6, we show the production of ^{149}Gd and ^{149}Eu . The analysis of the data caused a few more problems than those encountered for the earlier data. To begin with, the half-life of ^{149}Gd was not well known, so we followed the decay of the three most intense gamma rays in the ^{149}Gd decay: 149.7 keV (gamma-ray intensity, $I_\gamma = 49\%$), 298.6 keV ($I_\gamma = 28.3\%$), and 346.7 keV ($I_\gamma = 23.9\%$) for 115 d for two samples on two different counters. The data yield a half-life of 9.282 ± 0.008 d. There was some concern about what to use for I_γ . We found from the growth and decay of ^{149}Eu that our results were most

Figure 1. Excitation functions for $^{153}\text{Eu}(p,3n)^{151}\text{Gd}$ (squares) and $^{151}\text{Eu}(p,n)^{151}\text{Gd}$ (circles and triangles). Note that, to remove the (p,n) contribution to the ^{151}Gd data in the region of overlap, we normalized the high-energy tail to the $^{153}\text{Eu}(p,n)^{153}\text{Gd}$ data of Fig. 2 (shown by circles).

Figure 2. $^{153}\text{Eu}(p,n)^{153}\text{Gd}$ excitation function.

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consistent with that for the measurements of Sen and coworkers³ for the first gamma ray. (The other intensities were obtained from the normalization of our data.) The gamma rays used in the analysis of the ^{149}Eu data were 277.09 keV ($I_\gamma = 3.55 \pm 0.11\%$) and 327.53 keV ($I_\gamma = 4.03 \pm 0.12\%$), which are measurements of Meyer and coworkers.⁴ Figure 5 shows the proton data: $^{151}\text{Eu}(p,3n)^{149}\text{Gd}$ and $^{151}\text{Eu}(p,(p2n,dn,t))^{149}\text{Eu}$.

Figure 3. $^{151}\text{Eu}(d,2n)^{151}\text{Gd}$ (circles) and $^{153}\text{Eu}(d,4n)^{151}\text{Gd}$ (triangles) excitation functions.

Figure 5. $^{151}\text{Eu}(p,3n)^{149}\text{Gd}$ (triangles) and $^{151}\text{Eu}(p,(p2n,dn,t))^{149}\text{Eu}$ (circles) excitation functions.

Figure 6 shows the corresponding data: $^{151}\text{Eu}(d,4n)^{149}\text{Gd}$ and $^{151}\text{Eu}(d,(3np,2nd,nt))^{149}\text{Eu}$. For the ^{149}Eu production, reaction thresholds suggest probable contributions from the higher-order reactions.

Modeling

The $^{151}\text{Eu}(p,n)^{151}\text{Gd}$ and $^{153}\text{Eu}(p,n)^{153}\text{Gd}$ data have been studied in some detail. We found it necessary to resort to a coupled-channel

Figure 4. $^{153}\text{Eu}(d,2n)^{153}\text{Gd}$ excitation function.

Figure 6. $^{151}\text{Eu}(d,4n)^{149}\text{Gd}$ (triangles) and $^{151}\text{Eu}(d,(p3n,d2n,tn))^{149}\text{Eu}$ (circles) excitation functions.

calculation to allow for the shape differences between $^{151}\text{Eu}(\beta_2 = 0.13)$ and $^{153}\text{Eu}(\beta_2 = 0.28)$. A paper has been submitted to *Nuclear Physics Letters*,⁵ and an account is presented elsewhere in this *Annual Report*.⁶ The calculation needs to be extended to the deuteron data and to higher-order reactions.

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Effects of Nuclear Deformation on $^{151,153}\text{Eu}(p,n)^{151,153}\text{Gd}$ Reactions

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In a recent experiment, we used targets of natural europium to accurately measure the $^{151,153}\text{Eu}(p,n)^{151,153}\text{Gd}$ excitation functions between 5 and 12 MeV. We find that the cross sections for ^{153}Eu , $\sigma(153)$, in the rising portion of the excitation function are enhanced relative to those for ^{151}Eu , $\sigma(151)$. This observation is particularly interesting because it is consistent with nuclear structure work in the europium, $N = 89$, region. These studies document significant changes in nuclear properties as the result of a drastic change in the equilibrium ground-state shape. In this report (see also Ref. 1), we present evidence that the behavior of our measured cross sections is the result of the shape difference between ^{151}Eu ($\beta_2 = 0.13$) and ^{153}Eu ($\beta_2 = 0.28$). An observation similar to ours has been noted in neutron total cross-section measurements for the even-even neodymium and samarium isotopes.²

Table 1. Decay-scheme data for $^{151,153}\text{Gd}$.

	E (keV)	I_γ (%)
^{151}Gd ($t_{1/2} = 125.6$ d)	153.6	6.20
	174.7	2.98
	243.2	5.58
^{153}Gd ($t_{1/2} = 237.9$ d)	97.43	27.60
	103.18	20.45

Experimental Measurements

Our experiments were carried out at the tandem Van de Graaff facility at Centre d'Etudes, Bruyeres-le-Chatel, France (CEB). We used beams of protons in the energy range between 6 and 12 MeV to irradiate single- and multiple-foil stacks of specially fabricated targets of natural Eu_2O_3 . The targets were made by thoroughly mixing chemically pure Eu_2O_3 with a polyimide resin. The details of the target-making procedure have been described elsewhere in this *Annual Report*.³

The ^{151}Gd and ^{153}Gd gamma-ray activities from the foils were measured on large-volume germanium detectors at the radiation-counting facility of the CEB, and the data were analyzed by computer. Measured decay rates were converted to the number of gadolinium atoms produced during the irradiation by using the decay-scheme information in Table 1 and by using the isotopic-abundance values for natural europium of 47.8% for ^{151}Eu and 52.2% for ^{153}Eu .

Because the target foils had a total thickness of about 15 mg/cm², the beam suffered significant energy degradation during its passage through a single foil. We calculated the energy losses through individual foils and through foil stacks that were composed of as many as three europium foils interleaved with thin aluminum-degrader foils. The

energy loss through a typical foil was 0.4 to 0.6 MeV for 10-MeV protons. Depending on the number of foils in a stack, the losses could accumulate to several MeV at the lowest beam energies. To check the accuracy of our energy-loss calculations, we measured the energy loss experienced by protons through single foils and through foil stacks. These measurements were conducted at several incident particle energies between 3 and 12 MeV. The calibration spectrum of protons and the spectrum of 7.16-MeV protons after passing through a selected stack are shown in Fig. 1. The calculated energy loss for a foil stack that was significantly thicker than we used in our actual measurements agreed with the measured value to better than 3%. For thinner stacks of foils, the agreement was usually better than $\pm 1\%$.

The results of our measurements are shown in Fig. 2 as a plot of $[\sigma(153) - \sigma(151)]/\sigma(151)$ vs E , where E is the effective energy of the protons in the foils. The feature we want to emphasize in Fig. 2 is the clear enhancement of the ^{153}Eu cross sections relative to those measured for ^{151}Eu . The scatter of the data reflects uncertainties associated with individual foil uniformity, beam energy, beam-current integration, and counting statistics. Because we used foils that were homogeneous isotopic mixtures of ^{151}Eu and ^{153}Eu ,

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any uncertainty in proton energy would not alter the data comparison. However, the positions of the enhancement ratios on the energy scale are affected by energy errors, although these errors are ≤ 100 keV and are not significant in Fig. 2. In addition (see Table 1), for the ^{151}Gd data we have an uncertainty in gamma-ray intensity I_γ of $\pm 3\%$, and for ^{153}Gd an uncertainty of $\pm 5\%$. In Fig. 2, the shaded area represents the upper and lower bounds on our data that could result from the I_γ uncertainties. The other uncertainties discussed previously affect the data comparison in only a minor way.

Figure 1. Energy-loss measurements. (a) Proton-calibration spectra for energy-loss measurements. Each peak corresponds to an undegraded beam profile at the energy noted; the ordinate is logarithmic in the number of protons detected. (b) Profile of a 7.16-MeV proton beam after passing through a 7-mg/cm² aluminum degrader foil and a 14-mg/cm² plastic-europium target. For this combination, our calculated vs measured energy losses agree to within $\sim 0.01\%$.

In Fig. 2, we show also the results of our calculated enhancements from a spherical-optical-model calculation (SPH) and from coupled-channel calculations (CC) with deformed potentials. The enhancements calculated from the spherical statistical model are owing completely to the mass and isospin dependence in the optical potential and in the level-density prescription. These calculations miss the data by generally a factor of 3 and are, therefore, quite inadequate to account for our observations. By using the CC formalism with deformed potentials, however, we significantly improve the agreement for $E < 10$ MeV. We remark here, also, that our CC-calculated (p,n) excitation functions agree very well with the

experimental data at low energies but begin to depart noticeably from the measurements at $E \approx 9$ MeV.

The general disagreement between our calculations and experiment beyond 9 to 10 MeV results primarily from an improper characterization of the statistical model parameters associated with the (p,2n) competition. We have used only global optical potentials and the level densities from a Gilbert-Cameron prescription⁴ with parameters from Rose and Cook.⁵ Further refinements in the calculations will require a better characterization of these model features in the $A \approx 150$ region. Thus, with the present form of the calculations and given the approximations made, making parameter adjustments to better fit

Figure 2. The (p,n) cross-section differences for ^{153}Eu and ^{151}Eu , divided by the $^{151}\text{Eu}(p,n)$ cross section. The upper and lower bounds of the shaded area indicate the maximum range that could occur in the interpretation of the data because of uncertainties of $\pm 3\%$ in the values of I_γ for ^{151}Gd and $\pm 5\%$ for ^{153}Gd . The lines labeled CC and SPH refer to our theoretical calculations for coupled-channel and spherical-optical models, respectively.

the data at higher energies is unwarranted. Clearly, it would be most desirable to obtain the (p,n) cross sections for both nuclei from a statistical model that uses the coupled-channel formalism. At low energies, where we have good agreement with our calculations, there is only one minor competing channel, (p, γ), and the effect of the inelastic channels is relatively small. However, as the projectile energy increases, this coupling becomes progressively more important, and it would be expected to be a non-negligible feature in any realistic calculations for higher-energy (p,xn) processes.

Conclusion

We believe that our data provide an excellent and unique opportunity to test reaction-model calculations in spherical and deformed nuclei. In

addition to the data described here, we have also measured (d,2n) excitation functions for the same target nuclei. The data show enhancements for deuterons similar to those for protons. However, the analyses are still preliminary, and the results will be reported later. Additional data for $E > 11$ MeV for both protons and deuterons are also being acquired and will be used to identify any shape effects at higher energies by means of more-realistic, coupled-channel Hauser-Feshbach calculations.

Acknowledgments

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Coupled-Channel Calculations for Neutron- and Proton-Induced Reactions on Deformed Targets

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On the basis of geometric considerations, nuclear-reaction cross sections in deformed nuclei (rotational) are expected to be larger than those of spherical or vibrational nuclei.¹ This cross-section enhancement has been studied both experimentally^{2,3} and theoretically²⁻⁴ for total neutron cross sections and, more recently, for the (p,n) and (d,2n) cross sections for $^{151,153}\text{Eu}$.⁵ The (p,n) and (d,2n) data showed an enhancement up to 35% for the deformed nucleus ^{153}Eu ($\beta = 0.28$) compared with the vibrational

nucleus ^{151}Eu ($\beta = 0.13$) for $5 < E < 12$ MeV. This was about a factor of 3 larger than the enhancement found in the total neutron cross sections (including shape elastic) in other nuclei with similar deformations for the same energy range.^{2,3}

Recognizing that some of the extra enhancement in the (p,n) and (d,2n) cross sections may be caused by the fact that these cross sections are for specific exit channels, we suggested that the more likely explanation for the larger enhancement

for charged particles was the occurrence of Coulomb effects on top of the deformation effect. To establish this fact quantitatively, we performed coupled-channel calculations using the ECIS⁶ code for $^{151,153}\text{Eu}$ for neutrons and protons. We report our calculated results for two potentials: a global potential by Becchetti and Greenlees (BG)⁷ modified for (p,p') studies in europium⁸ and a recently evaluated potential for europium by Macklin and Young (MY).^{9,10} Details will follow, but we

briefly mention that the enhancements for proton reaction cross sections are, in general, larger than those for neutrons, independent of the choice of potential used in the calculations. The exceptions to this are the inelastic cross sections. We also compare the absolute values of the inelastic and compound cross sections calculated with the two potentials.

Cross-Section Calculations

The reaction cross sections were calculated by using the 1979 version of the coupled-channel code ECIS,⁶ available on our Cray computers. We used the symmetric rotational model for ¹⁵³Eu and both a symmetric rotational model and a first-order vibrational model for ¹⁵¹Eu, depending on the choice of the deformed potential. Three or four levels are allowed to be coupled in the calculations. The properties of these levels are given in Table 1, at the bottom of

which we also give the deformation parameters and identify the specific potential used. The potentials themselves are given in Table 2 for BG^{7,8} and in Table 3 for MY.^{9,10} Both of these potentials, with their own deformed parameters, were used independently to study different

reaction properties of ^{151,153}Eu. For example, Lanier and coworkers⁸ used a modified BG potential for the analysis of (p,p') on ¹⁵¹⁻¹⁵³Eu, and Macklin and Young⁹ used their potential to investigate neutron capture in ^{151,153}Eu. We discuss later their relative appropriateness.

Table 1. Spins, parities, and energies of coupled levels in ^{151,153}Eu, together with the models and associated potentials.

¹⁵¹ Eu (vibrational model)		¹⁵¹ Eu (rotational model)		¹⁵³ Eu (rotational model)	
E (keV)	I ^π	E (keV)	I ^π	E (keV)	I ^π
0	5/2 ⁺	0	5/2 ⁺	0	5/2 ⁺
196	3/2 ⁺	308	7/2 ⁺	83	7/2 ⁺
308	5/2 ⁺	503	9/2 ⁺	193	9/2 ⁺
506	7/2 ⁺				
β ₂ = 0.13, β ₄ = 0.0 (BG potential)		β ₂ = 0.16, β ₄ = 0.0 (MY potential)		β ₂ = 0.28, β ₄ = 0.06 (BG potential)	
				β ₂ = 0.30, β ₄ = 0.0 (MY potential)	

Table 2. Deformed optical-model parameters for ^{151,153}Eu for the Becchetti-Greenlees (BG) potential for neutrons and protons.^a

Potential (MeV)	r _i , a _i (fm)
Neutrons	
V _R = 56.3 - 24η - 0.32E	1.17, 0.75
W _D = (13 - 12η - 0.25E)0.8	1.26, 0.58
W _V = (-1.56 + 0.22E)0.8	1.26, 0.58
V _{SO} = 6.2	1.01, 0.75
Protons	
V _R = 54.0 + 24η - 0.32E + ΔV _C	1.17, 0.75
W _D = (11.8 + 12η - 0.25E)0.8	1.32, 0.51 + 0.7η
W _V = (-2.7 + 0.22E)0.8	1.32, 0.51 + 0.7η
V _{SO} = 6.2	1.01, 0.75
	r _c = 1.25
η = (N - Z)/A, ΔV _C = 0.4(Z/A ^{1/3})	
β ₂ = 0.13, β ₄ = 0.0 (¹⁵¹ Eu)	
β ₂ = 0.28, β ₄ = 0.06 (¹⁵³ Eu)	

^a Note that the imaginary potentials are reduced by 20%.

Table 3. Deformed optical model parameters for ^{151,153}Eu.^a

Potential (MeV)	r _i , a _i (fm)
V _R = 49.8 ± 16η - 0.40E + ΔV _C	1.28, 0.63
W _D = 4.02 ± 8η + 0.51E, E < 10	1.28, 0.48
W _D = 9.12 ± 8η - 0.09(E - 10), E > 10	1.28, 0.48
W _V = 0.0, E < 8	1.28, 0.63
W _V = -2.0 + 0.25E, E > 8	1.28, 0.63
V _{SO} = 6.0	1.28, 0.63
	r _c = 1.28
η = (N - Z)/A, ΔV _C = 0.4(Z/A ^{1/3})	
β ₂ = 0.16, β ₄ = 0.0 (¹⁵¹ Eu)	
β ₂ = 0.30, β ₄ = 0.0 (¹⁵³ Eu)	

^a The ± signs denote protons and neutrons, respectively. Note that the energy dependence of the real potential is different from the published value.⁹ This is the preferred value, according to Young.¹⁰

Numerical parameters used in the calculation included 0.1 fm for the integration mesh size, 21 and 17.5 fm for the respective matching radii for protons and neutrons, $30\hbar$ for the maximum channel spin, and 10^{-5} for the iteration-convergence criterion.

Results

The results are shown in Figs. 1 through 4 and Table 4. In Fig. 1, we show the cross-section ratios, $\sigma(^{153}\text{Eu})/\sigma(^{151}\text{Eu})$, calculated with the modified BG potential. The ratios are shown separately for the compound, inelastic, and total (sum of the two) reaction cross sections. Similar ratios for the MY potential are shown in Fig. 2. The larger ratio for ^{153}Eu , as seen in these two figures, is caused by two effects: the larger size and the larger deformation of ^{153}Eu . The size effect is at most 5% and is not shown here separately. The enhancement of ^{153}Eu compared with ^{151}Eu is, therefore, mainly the result of the larger deformation of ^{153}Eu .

When proton ratios are compared with neutrons, we clearly find a greater enhancement for the protons for the compound and total cross sections. This is true for both the potentials, although the magnitudes are different. We expect it to be a general property for deformed nuclei, and it can be attributed to the Coulomb and deformation effects. The exceptions to this are the inelastic cross sections. Most of the difference in the inelastic ratios of Figs. 1 and 2 can be attributed to the fact that ^{151}Eu is treated as a vibrator in Fig. 1 and a rotor in Fig. 2. Some of the effects, of course, occur because the radius parameters of the two potentials are greatly different.

For completeness, the absolute values of the cross sections are

Figure 1. Cross-section ratios, $\sigma(^{153}\text{Eu})/\sigma(^{151}\text{Eu})$, calculated with the BG deformed potential. The (a) compound, (b) inelastic, and (c) total cross sections are compared for neutrons and protons. A smooth line is drawn between calculated points.

shown in Fig. 3 for the proton reactions on ^{153}Eu . The neutron cross sections are shown in Fig. 4. The result to notice is that the neutron inelastic cross sections for the MY potential are larger than for the BG potential. The results are similar for ^{151}Eu .

Discussion

On the basis of our present experience and a review of the published literature, we conclude that the deformation-dependent cross-section enhancement for the compound and total reaction cross sections is larger for protons than for neutrons. The exceptions to this are the inelastic cross sections. Since both the BG and MY potentials previously were used successfully to explain different

measured properties of europium, it is natural to ask the question: "Of the two potentials, which is the more appropriate for europium?" Of course, we cannot answer that yet. However, one constraint used to choose the MY potential parameters is that the coupled-channel calculations reproduce the experimental total cross section (including shape elastic) for natural europium. We compare, in Table 4, such total cross sections for the two potentials. The table shows that the total cross section is not a sensitive measure of the potentials. Clearly, the quantity that seems to be most sensitive either to the coupled-channel model or the potential is the inelastic cross section, which we plan to study further.

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Figure 2. Cross-section ratios, $\sigma(^{153}\text{Eu})/\sigma(^{151}\text{Eu})$, calculated with the MY deformed potential. The (a) compound, (b) inelastic, and (c) total cross sections are compared for neutrons and protons. A smooth line is drawn between calculated points.

Figure 3. Absolute values of the compound and inelastic cross sections for $p + ^{153}\text{Eu}$. The BG and MY values are compared. A smooth line is drawn between calculated points.

Figure 4. Absolute values of the compound and inelastic cross sections for $n + ^{153}\text{Eu}$. The BG and MY values are compared. A smooth line is drawn between calculated points.

Table 4. Total cross sections (including shape elastic) for BG and MY potentials for n + natural europium (47.9% ^{151}Eu + 52.1% ^{153}Eu).

E_n (MeV)	$\sigma_{\text{tot}}(\text{BG})$ (b)	$\sigma_{\text{tot}}(\text{MY})$ (b)	$\frac{\sigma_{\text{tot}}(\text{MY})}{\sigma_{\text{tot}}(\text{BG})}$
4	5.643	5.680	1.007
5	5.215	5.155	0.988
6	4.915	4.863	0.989
8	4.705	4.757	1.011
10	4.777	4.934	1.033
12	4.912	5.106	1.039

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Models for Deuteron-Induced Reactions

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Nuclear cross sections below $E \leq 20$ MeV are usually calculated by using the Hauser-Feshbach statistical theory.¹ An important ingredient in these calculations is the compound-nucleus cross section or transmission coefficient for each angular momentum. These partial cross sections are routinely taken from an optical model. However, for the deuteron-induced reactions (and also for reactions involving other composite projectiles, such as tritons and helium nuclei), a large fraction of the reaction cross section is in the breakup of the incident particle. The breakup cross sections must be subtracted from those of the optical-model reactions for each angular momentum before Hauser-Feshbach emissions can be calculated. For this purpose, we have developed a phenomenological model.² The purpose of this paper

is to examine the consistency of the predictions of this model with those of a more complicated microscopic model^{3,4} for the reaction $d + {}^{93}\text{Nb}$ below 25 MeV. The microscopic model itself is tested against the available data. The details will follow, but we summarize our main results here. We show that the phenomenological model can reliably account for all direct-reaction cross sections, including the breakup, and can provide the input for the Hauser-Feshbach calculations.

The Models

Both the microscopic and phenomenological models are based on direct-reaction theory. However, there are differences in the two models, both in physics and in the degree of complexity in the calculation. For example, the phenomenological model is simple and closely

tied to the optical model; however, we can calculate only the angle- and energy-integrated cross sections in the entrance channel, and not the emission spectra and angular distributions. In contrast, we can calculate all of these quantities with the microscopic model, but the calculations are complicated and time-consuming. We provide only a brief description of the two models here.

Phenomenological Model. This model is referred to in the literature⁵ as the direct-reaction approach to fusion (DRAF), and it is closely tied to the optical model for particle a incident on target A . The model has two parts. The first is to split the imaginary part of the optical potential, W , into an inner part, W_F (fusion potential), and an outer part, W_D (direct-reaction potential). The second is to associate W_F with fusion

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reaction and W_D with direct reactions, including breakup, breakup fusion, and any incomplete fusion processes. Thus, we can write:

$$W_F = \begin{cases} W & \text{for } r < R_F \\ 0 & \text{for } r > R_F \end{cases} \quad (1)$$

and

$$W_D = W - W_F, \quad (2)$$

where $R_F = r_F A^{1/3}$, and A is the mass number. The cross sections for the fusion and direct reactions are then given by the standard optical-model expression:

$$\sigma_i^{\text{DRAF}} = \frac{2}{\hbar v_a} \langle \chi_a^{(+)} | -W_i | \chi_a^{(+)} \rangle, \quad (i = F \text{ and } D), \quad (3)$$

where v_a is the incident velocity, and $\chi^{(+)}$ is the distorted wave in which the full imaginary potential W is taken into account.

The distorted wave $\chi^{(+)}$ can be expanded into partial waves as:

$$\chi_a^{(+)} = \frac{1}{k_a r} \times \sum_{\ell=0}^{\infty} i^{\ell} (2\ell + 1) \chi_{\ell}(r) P_{\ell}(\theta), \quad (4)$$

where k_a is the wave number. The function $P_{\ell}(\theta)$ is the Legendre polynomial. By using Eq. (4), we can write the expression in Eq. (3) as:

$$\sigma_i^{\text{DRAF}} = \frac{\pi}{k_a^2} \sum_{\ell=0}^{\infty} (2\ell + 1) T_{\ell,i}, \quad (i = F \text{ and } D), \quad (5)$$

with the transmission coefficient $T_{\ell,i}$ given by:

$$T_{\ell,i} = \left(\frac{8}{\hbar v_a} \right) \times \int_0^{\infty} |\chi_{\ell}(r)|^2 W_i(r) dr. \quad (6)$$

As is evident, the total reaction cross section, σ_R , is given as a sum of σ_F and σ_D . Note that σ_D contains all direct-reaction cross sections, including breakup, and σ_F is the fusion or absorption cross section normally associated with the Hauser-Feshbach model. The cross section σ_D is small at lower energies, except for the composite projectiles.

Thus, the main ingredients in the phenomenological DRAF method are the choice of the imaginary part of the optical potential, W , and the fusion-radius parameter, r_F . Note that the real optical potential also plays a role in this method and is used in calculating the distorted wave.

Microscopic Model. We discuss here only the elastic-breakup (EB) and breakup-fusion (BF) processes but not the inelastic scattering processes. Usually, the contributions from all of these processes should be combined and compared with the σ_D of the previous subsection.

The EB and BF reactions may be written symbolically as:

The first step stands for the EB of the incident particle a into $b + x$. (If a is the deuteron, then b is a proton and x is a neutron, or vice versa.)

The BF involves first the breakup and then the subsequent partial fusion of x into the target A .

We first write down the double differential cross section for the EB reaction (i.e., the cross section for observing b coming from the first stage of the reaction). It is given by the well-known distorted-wave Born approximation (DWBA) expression⁶ as:

$$\frac{d^2\sigma^{\text{EB}}}{dE_b d\Omega_b} = \frac{2\pi}{\hbar v_a} \rho(E_b) \rho(E_x) \times \langle \chi_b^{(-)} \chi_x^{(-)} | V_a | \chi_a^{(+)} \phi_a \rangle|^2. \quad (8)$$

Here, v_a is the incident velocity, E_b and E_x are the energies of b and x particles, respectively, and $\rho(E_i)$ ($i = b$ or x) is the phase-space volume for the outgoing particle, i . They are related through:

$$E_b + E_x = E_a + Q, \quad (9)$$

where E_a is the incident energy, and Q is the Q value of the three-body breakup. Further, $\chi^{(+)}$ and $\chi^{(-)}$ are the distorted waves for the incident particle, a , and the outgoing particle, i , respectively. The function ϕ_a stands for the spatial part of the projectile's internal wave function, while the interaction potential, V_a , is given by:

$$V_a = U_b + U_x - U_a. \quad (10)$$

In Eq. (10), U_a , U_b , and U_x are the optical potentials for the particles, a , b , and x , respectively.

We now turn to the BF cross-section formula. We start with the double differential cross section. It is given¹ as an expectation value of the imaginary part, W_x , of U_x with

respect to the wave function, ψ_x , for $(x + A)$ as:

$$\frac{d^2 \sigma_{\text{BF}}}{dE_b d\Omega_b} = \frac{2}{\hbar v_a} \times \rho(E_b) \langle \psi_x | -W_x | \psi_x \rangle, \quad (11)$$

where ψ_x describes the motion of the particle x (to be eventually absorbed) relative to the target. It satisfies the following inhomogeneous equation:

$$(E - T_x - U_x)\psi_x = (\chi_b^{(-)} | V_a | \chi_a^{(+)} \phi_a \rangle. \quad (12)$$

The matrix element on the right-hand side of Eq. (12) implies a five-dimensional integral that is closely related to the six-dimensional integral of Eq. (8). This is often called the "source function," which represents the strength of producing x at the time when the breakup occurs.

The above is only a sketch of the EB and BF processes. The formulations are based on direct-reaction theory, and the interactions are given by the optical potential.

Calculated Results

The cross sections have been calculated using both the phenomenological and microscopic models for the $d + {}^{93}\text{Nb}$ system. The main inputs in the phenomenological model calculations are the entrance-channel optical potential for deuterons and the fusion-radius

parameter, r_F . The EB and BF calculations require the neutron and proton optical potentials in addition to the deuteron potential. We use the standard form for these potentials; however, we neglect the energy dependence in the present calculations. The values of the potential parameters used in the calculation are taken from the compilation by Perey and Perey⁷ and are summarized in Table 1. The choice of the parameter r_F is described later.

We first show the microscopic-model results for (d,px) spectra and angular distributions for two incident energies of $E_d = 15$ and 25.5 MeV, where experimental data are available. Note that the (d,px) cross sections are the sum of EB, in which both proton and neutrons emerge, and BF, in which the neutron is captured by the target while the proton emerges. Two energy spectra, $d\sigma_p/dE_p$, of protons are shown in Fig. 1 and compared with experimental data.^{8,9} The angular distributions of $d^2\sigma_p/(dE_p d\Omega_p)$ are shown in Fig. 2, where they are also compared with data.^{8,9} Note that both of these quantities can be calculated only by the microscopic model. Our results show excellent agreement between the predictions of the microscopic model and the experimental data.

The cross sections obtained by the use of the phenomenological model were calculated with the deuteron potential shown in Table 1 and with $r_F = 1.58$ fm. The value of this

parameter was chosen by matching total breakup plus the (d,d') cross sections for $E_d = 25.5$ MeV with the σ_d^{DRAF} given by Eq. (3). We then calculated σ_d^{DRAF} for other energies with this fixed value of r_F . The results are shown in Fig. 3. We also include the sum of the EB, BF, and (d,d') cross sections, shown in Fig. 3 as σ_d^{BUDR} . The agreement between the two theoretical DR cross sections is very good, which indicates that the two methods used are mutually consistent. This further indicates that when we are interested in calculating only the total DR (or equivalently, fusion) cross section, we can use the DRAF method, which is much simpler than the microscopic breakup and (d,d') calculations. Note that we have not discussed (d,d') calculations here but have used the multistep direct reaction (MSDR) approach of Tamura et al.¹⁰

Conclusions

We have briefly described a phenomenological model (DRAF) and a microscopic model (EB and BF) for calculating cross sections for

Figure 1. Energy spectra of protons emitted in the ${}^{93}\text{Nb}(d,p)$ reaction, for deuteron bombarding energies of 15 to 25.5 MeV.

Table 1. Optical-potential parameters used in the calculations.

Particle	V (MeV)	W_D (MeV)	a (fm)	a_D (fm)	r (fm)	r_D (fm)	r_C (fm)
d	99.0	16.7	0.84	0.64	1.12	1.31	1.30
p	50.6	14.1	0.678	0.47	1.25	1.25	1.25
n	48.8	9.76	0.68	0.48	1.22	1.13	—

deuteron-induced reactions. We carried out microscopic calculations for the $d + {}^{93}\text{Nb}$ system with incident energies of about 10 to 25 MeV. When we tested the results of the calculations against existing experimental data, we found that the calculated cross sections fit the existing data very well.

We have determined the value of r_F to be 1.58 fm, which is larger than the value of 1.45 fm determined for the heavy-ion reactions.^{3,4} Using the r_F value thus determined, we made DRAF calculations of σ_D at other energies, $E_d = 10$ to 25 MeV, and compared these values with those from the microscopic model.

Figure 2. Angular distributions of protons emitted with 10 and 15 MeV in the ${}^{93}\text{Nb}(d,p)$ reaction, for deuteron bombarding energies of 15 and 25.5 MeV, respectively.

The excellent agreement between these results indicates that the DRAF method may be used reliably to calculate σ_D and consequently σ_F , the latter being an important input parameter to the Hauser-Feshbach calculations. Furthermore, calculations with the DRAF method can be done with any standard optical model-code.

Despite the present success in the use of the simpler DRAF method to account for direct reactions, including breakup, the main unknown quantity in this approach is the cutoff parameter, r_F . Our previous applications of this method to isomer-production cross sections² required a larger value of r_F (1.96 fm). This difference must be resolved. Also, application of the method to energies below 10 MeV requires a better knowledge of the low-energy deuteron potentials, which will require further investigation.

Figure 3. Cross sections obtained from DRAF compared with those obtained from the EB, BF, and MSDR methods.

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Cross Sections for (p,n) and (d,2n) Reactions on ^{79}Br and ^{127}I : An Evaluation of Results from Selected Literature and from Model Calculations

R. G. Lanier, M. G. Mustafa, and H. I. West, Jr.

Because of current interest in ^{79}Br and ^{127}I as charged-particle detectors in nuclear device diagnostics, we have performed an evaluation of the relevant cross sections. This work has provided interim cross-section sets for ^{79}Br and ^{127}I and also

the background data necessary for future measurements. Because of the success of our recent measurements^{1,2} of (p,n) and (d,2n) excitation functions on europium nuclei, we believe we have developed³ a simple but effective target-making

technology that we can apply to other difficult materials. Thus, it seems now possible to make very good cross-section measurements of the rather difficult halogen species bromine and iodine.

We present here the condensed, edited, and evaluated data obtained from our literature search. The evaluations were aided by our experience with developing the titanium and chromium cross-section sets and are derived, in part, from statistical-model calculations that incorporate, in particular, our understanding of deuteron breakup as it applies to cross sections at low energies. The LLNL Technical Information Department did a computer search of the literature for the years 1935 through 1988 through the National Nuclear Data Center archives. For the years between 1976 and 1988, this information was supplemented by references obtained from the *Charged Particle Nuclear Data Bibliography*, published by the Brookhaven National Laboratory.

Results

The results of our evaluations for the (p,n) and (d,2n) excitation functions for ^{79}Br and ^{127}I are given in Tables 1 and 2, which include both experimental and calculated results. In Figs. 1 and 2, we show much of the data and plot the results of our statistical-model calculations. The various sources from which the data originated are shown in the figures; the source named first in each figure is the primary source.⁴

Table 1. Cross sections for $^{79}\text{Br}(p,n)^{79}\text{Kr}$ and $^{79}\text{Br}(d,2n)^{79}\text{Kr}$.

$^{79}\text{Br}(p,n)^{79}\text{Kr}$					
No.	E_p (MeV)	$\sigma(p,n)$ (mb)	No.	E_p (MeV)	$\sigma(p,n)$ (mb)
1	2.47	0.11 ^a	9	7.76	442
2	2.97	3.91	10	8.83	545
3	3.48	13.7	11	9.92	626
4	3.98	33.6	12	10.98	724
5	4.33	52 ^b	13	12.13	646
6	5.55	160	14	13.12	521
7	6.70	328	15	14.11	434
8	7.13	394	16	16.69	158
$^{79}\text{Br}(d,2n)^{79}\text{Kr}$					
No.	E_d (MeV)	$\sigma(d,2n)^c$ (mb)	No.	E_d (MeV)	$\sigma(d,2n)^c$ (mb)
1	4.78	0.005	12	6.96	277
2	4.88	0.16	13	7.52	389
3	4.99	0.96	14	7.93	467
4	5.01	1.54	15	8.55	574
5	5.22	7.7	16	8.96	637
6	5.52	32	17	9.57	721
7	5.73	56	18	9.98	769
8	6.04	104	19	11.01	868
9	6.24	140	20	12.03	943
10	6.55	197	21	13.06	999
11	6.75	236	22	14.09	1043

^a Cross-section values between 2.47 and 3.98 MeV are taken from STAPRE calculations and fit the existing data between 4.33 and 7.13 MeV quite well.

^b Experimental data are given for energies between 4.33 and 16.69 MeV.

^c No data available. The values given here are obtained from a STAPRE calculation but are reduced by 20% to account for deuteron breakup. This reduction is based on our experience with understanding the (d,2n) reaction on chromium and titanium.

Cross-section measurements at low energies, and where the excitation function rises rapidly, are difficult to make and are susceptible to many uncertainties. In our experiments, we always make multiple measurements and check our consistency by comparing results at the same energy with thin and thick targets. In general, the measurements currently described in the literature are not done with the same level of

care. Thus, although the errors quoted by most authors are realistic when applied to excitation-function data at high energies, they tend to be somewhat optimistic when applied to measured values near threshold. Moreover, because modern measurements now tend to emphasize radionuclide production for medical applications, an accurate cross-section measurement, when such a value is small, is not a particularly

important component of that research. For those reasons, and because there simply are not many data on the rising portion of the excitation functions, we have used model calculations to fill in these gaps.

Although particular uncertainties are associated with applying such calculations to bromine and iodine, we believe our calculated values, when combined with existing data, offer a more reasonable estimate

Figure 1. Bromine excitation functions. (a) ⁷⁹Br(p,n)⁷⁹Kr cross sections. Our adopted values are shown with measured data from the literature and our calculated values. (b) ⁷⁹Br(d,2n)⁷⁹Kr cross sections. No measured data are available. Our adopted values are shown with our calculated values.

Figure 2. Iodine excitation functions. (a) ¹²⁷I(p,n)¹²⁷Xe cross sections. (b) ¹²⁷I(d,2n)¹²⁷Xe cross sections. Our adopted values are shown with measured data from the literature and our calculated values.

of the cross sections than simple extrapolations or other ad hoc numerical manipulations. For the (d,2n) cross sections, we relied completely on the calculations from the STAPRE and ALICE codes with global parameters. In the rising portion of the excitation functions, the two codes gave similar cross sections, although the physics used is different.

Virtually all of the measurements discussed were done with a stacked-foil technique. This is a standard measurement, but it suffers from the drawback that the energy deposited in a foil must be calculated by an energy-loss prescription. Error propagation due to the energy-loss calculations can be reduced considerably if one uses few foils per stack and if each foil is reasonably thin.

Table 2. Cross sections for $^{127}\text{I}(\text{p},\text{n})^{127}\text{Xe}$ and $^{127}\text{I}(\text{d},2\text{n})^{127}\text{Xe}$.

$^{127}\text{I}(\text{p},\text{n})^{127}\text{Xe}$					
No.	E_{p} (MeV)	$\sigma(\text{p},\text{n})$ (mb)	No.	E_{p} (MeV)	$\sigma(\text{p},\text{n})$ (mb)
1	3.01	0.08 ^a	10	7.14	135
2	3.5	0.28	11	7.77	196
3	4.0	0.89	12	8.78	362
4	4.34	1.61	13	8.93	375
5	4.5	3.15	14	9.92	457
6	5.0	8.9	15	10.98	384
7	5.56	20.3	16	12.13	305
8	6.0	42.4	17	13.15	193
9	6.70	86.3 ^b	18	14.12	134

$^{127}\text{I}(\text{d},2\text{n})^{127}\text{Xe}$					
No.	E_{d} (MeV)	$\sigma(\text{d},2\text{n})^{\text{c}}$ (mb)	No.	E_{d} (MeV)	$\sigma(\text{d},2\text{n})^{\text{c}}$ (mb)
1	3.91	0.001	10	8.58	328
2	4.52	0.16	11	8.99	394
3	4.93	1.04	12	9.60	490
4	5.54	7.1	13	10.01	550
5	5.94	18	14	11.02	685
6	6.55	53	15	12.04	796
7	6.96	91	16	13.05	863
8	7.57	169	17	14.07	879
9	7.98	230	18	15.09	878

^a Cross sections between 3.01 and 6.0 MeV are taken from STAPRE calculations except for the points at 4.34 and 5.56 MeV. At these points, the calculated/measured points agree to better than 3%; therefore, we have kept the measured values.

^b Experimental data are given for points between 6.70 and 14.12 MeV.

^c The cross-section values noted here are taken from STAPRE calculations reduced by 25% to account for deuteron breakup. The experimental data available for this reaction are highly uncertain and have not been used in our evaluation.

We identified as primary references those articles that described experiments in which we believe that some care was taken to minimize this kind of error propagation.

Secondary references include sets of measurements intended primarily for medical applications or describe experiments that, for other reasons, provide less-accurate data.

Finally, in Figs. 1 and 2, we have also plotted some of the data from our secondary sources. This is done to emphasize what we believe are essentially consistent results among all the experiments. The plots further emphasize the paucity of data at low energies; for all of the isotopes considered here, only eight data points are available for $E < 7$ MeV.

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Irradiation Facility at the LLNL Van de Graaff

H. I. West, Jr., K. B. Pedersen, D. H. Tinoco, and S. C. Peterson

As part of a project to measure charged-particle excitation functions for radiochemical diagnostics of nuclear tests, we irradiate stacks of foils at LLNL's new tandem Van de Graaff accelerator facility. The facility was built without radiation shielding (in the interest of economy), which means that each experimenter must provide personnel shielding as needed. In our case, we must shield personnel from neutrons and gamma rays produced in our targets during some fairly high-level irradiations.

The most extreme case for us is the rather copious quantities of MeV neutrons that are produced when beams of 20-MeV deuterons of 1- μ A intensity come to rest in beam stops of aluminum. A second facet of the work is that many of our targets consist of a plastic matrix containing

the material of interest (e.g., iodine and bromine). To minimize the local heat loading of the foils and to average over any small nonuniformities in the foils, we must raster the beam over the target within a region about 8×8 mm. Because we want to raster the beam fairly rapidly, we

believe that there are fewer design problems with an electrostatic sweeping system than with a magnetic system.

The location of our facility (Fig. 1) is 26.2 m from the operator's console, which is located at the front end of the Van de Graaff. Figure 2

Figure 1. Schematic of the Van de Graaff room, showing the location of our irradiation facility.

Figure 2. Details of the irradiation facility, indicating the location of functional parts.

shows the details of our setup, including the beam scanners, shielding, and target chamber. Figure 3 is a photograph of our experimental equipment.

Details of the Irradiation Facility

The amount of shielding needed is dictated by two requirements: (1) to keep the neutron level at the LLNL perimeter fence below 0.25 mrem and (2) to keep the fast flux (>1 MeV) of neutrons at the location of the Van de Graaff operator below 2.5 mrem ($\sim 20/\text{cm}^2\cdot\text{s}$). The major problem is minimizing the neutron flux at the operator. (Shielding for gamma radiation is a far less serious problem.) Initially, doing detailed calculations of the neutron transport problem as an aid to the shield design seemed to be an impossible task. In developing our approach to the problem, we made an unshielded run with 8-MeV protons into an aluminum beam stop,

which gave a neutron dose rate of about 1 mrem at the operator's console. Calculations obtained by using the ALICE code (M. Blann, Lawrence Livermore National Laboratory, private communication, 1989) gave a neutron production rate of 8×10^8 neutrons/s· μA for 8-MeV protons and 1.1×10^{11} neutrons/s· μA for 20-MeV deuterons. These numbers, which should be good to within a factor of 2, helped determine the design of the shield.

We first considered a shield design with a cylindrical geometry consisting of an outer shell of lead and a thick inner shell of borated polyethylene. Because that design required heavy castings and nonstandard sizes, we found it to be considerably more costly than a square geometry (which we finally selected), which enabled us to use standard 1- and 2-in. sheets. To minimize weight, we placed half of the lead (1 in.) next to the target, where it attenuates the target gamma rays and, to a lesser

extent, moderates neutrons. The other half is placed on the outside of the shield, where it attenuates 2.23-MeV neutron-capture gamma rays on hydrogen and further attenuates the target gamma rays.

In the forward direction (the direction in which the fast neutrons are emitted), up to 10 in. of borated polyethylene is used. In the opposite direction, surrounding the beamline, is another 10 in. or more of borated polyethylene shielding. We may even have to add shielding internal to the beamline if backstreaming becomes a problem. Perpendicular to the beamline at the target is the least amount of borated polyethylene (8 in.) used in the shielding. However, because of the square cross section, it is a simple matter to attach extra shielding to the exterior of the shield if needed.

To raster the beam over the target, we apply sawtooth voltages to the two sets of 1-m-long deflection electrodes (shown at the far left in Fig. 2). A balanced drive to the electrodes is preferred. A 2-cm gap is used. For a target located 2.5 m from the end of the deflecting plate, we need a 2000-V sweep for 20-MeV protons to give a 5-mm scan on the target. (One can easily scale for other particles and energies.) We use asynchronous sweep frequencies of about 9 and 100 Hz. The voltages are supplied by high-voltage operational amplifiers, driven by signals in the range of 0 to 10 V and controlled from the operator's console.

Moving to the right along the beamline in Fig. 2, we next encounter a set of magnetic dipoles used for passive steering. Next in line is a beam locator, followed by an electropneumatic gate valve. The valve is interlocked with the pressure gauge to ensure against inadvertent operation. Vacuum is supplied by a turbopump, backed

Figure 3. Photograph of the experimental apparatus. See Fig. 2 to identify the details.

up by a roughing pump. The beamline continues to the right into the shield housing, which is made of three easily movable, rail-mounted sections. (The last section is removable for access to the target chamber.) The irradiation chamber is separated from the beamline by an insulating section and provides the function of a Faraday cup. The current into the Faraday cup is measured by a digital current integrator located at the operator's console. The unit is capable of high precision (about $\pm 0.2\%$ error). The target is cooled during irradiation by compressed air. To help in setting up for a run, we replace the target with a quartz plate and remove the end plug in the shield. The beam is positioned by means of the beam

locator at the input to the shield, and a television camera views the quartz plate to verify the alignment. Only after the beam is focused and centered are the raster voltages turned on and set.

Conclusion

We are using the apparatus to measure the iodine and bromine (p,n) and (d,2n) excitation functions. We also plan to finish our study of the europium cross sections at 12 to 20 MeV to complement the measurements at low energies made at Bruyères-le-Chatel, France, and at high energies made at the Crocker Nuclear Laboratory at the University of California at Davis. The facility is a permanent installation that will be used by others.

On the Interpretation of Ion-Range Data Obtained during Stacked-Foil Excitation-Function Measurements

H. I. West, Jr., and M. G. Mustafa

In the course of making excitation-function measurements by the stacked-foil method, one can measure the number of transformed ions recoiling out of the back of the primary targets by using catcher foils and, from these data, obtain the range of ions in the target foils. Typical data are shown in Figs. 1 and 2 for the $^{89}\text{Y}(p,n)^{89}\text{Zr}$ and $^{89}\text{Y}(d,2n)^{89}\text{Zr}$ reactions, respectively. In these figures, the respective excitation functions are shown as dashed lines. Clearly, even without resorting to calculation, we would argue in Fig. 1 that the ^{89}Zr ions

received full momentum transfer for proton energies (up to 17 or 18 MeV) to the region well past the statistical peak of the reaction. In contrast, the (d,2n) data show breakaway from what would be perceived to be full momentum transfer just past the statistical peak. These observations hold, in general, for other reactions that we have studied in chromium and titanium. We have developed a code that does the detailed kinematics for the reaction with emphasis on the recoil ion,¹ and we recently took a marked step forward in our interpretation of the results. Here we present our results for yttrium.

Calculations and Results

The range of a given ion is determined using the theory of Lindhard, Scharff, and Schiøtt (LSS).^{2,3} An angular distribution in the center of mass (CM) is assumed. The kinematics are established using Q values adjusted for loss of energy by gamma-ray emission during the reaction. Our calculation is carried out as follows. First, the maximum range R_m for an ion is determined. The calculation is then carried out in the CM system in steps of $x = R_m/100$ from the back of the foil, including all angles (0 to 180 deg in 1-deg steps). Tests as to whether the

Figure 1. $^{89}\text{Y}(p,n)^{89}\text{Zr}$ range-energy data. The data points are experimental data. The dashed curve is the excitation function for comparison with the range-energy data. The scales to the right give the fraction of MSD (f_{MSD}) and the averaged parallel momentum of the recoil ion in the center of mass.

ion escapes, using LSS theory, are conducted in the laboratory frame. We then determine the mean fractional range from:

$$R_f = R_m \frac{(\text{Number of escaping ions})}{(\text{Number of test ions})} \quad (1)$$

This is the number that should compare with our range-energy data.

To do a proper calculation, we need a realistic angular distribution. We have had success using the form:

$$\frac{1}{\pi - \theta} \exp[-C(\pi - \theta)^2], \quad (2)$$

(where C is a constant) for direct reactions, a constant for isotropy (compound), and a combination of both forms in regions where both compound and direct reactions occur. However, Kalbach,⁴ from the study of reaction systematics, has found a general phenomenological model that works well for our data and that would seem to embrace some of the physics involved. The angular distribution, which we use here, is written as:

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi} \frac{a}{\sinh(a)} [\cosh(a \cos\theta) + f_{\text{MSD}} \sinh(a \cos\theta)] \quad (3)$$

f_{MSD} controls fraction of multistep direct. For $f_{\text{MSD}} = 1$, the reaction is all multistep direct, and with

Figure 2. $^{89}\text{Y}(d,2n)^{89}\text{Zr}$ range-energy data. The data points are experimental data. The dashed curve is the excitation function for comparison with the range-energy data. The scales to the right give the fraction of MSD (f_{MSD}) and the averaged parallel momentum of the recoil ion in the center of mass.

$f_{\text{MSD}} = 0$, the reaction is all multistep compound. The parameter a is given approximately by:

$$a = k(E_b + S_b) , \quad (4)$$

in which E_b is the CM energy of the ejectile, and S_b is its separation energy. In our case, we use an equivalent form:

$$a = k(E_x - \bar{E}_\gamma) , \quad (5)$$

in which E_x is the excitation energy and $\bar{E}_\gamma$ is the average energy of the gamma rays emitted in the reaction. Here, we have changed from discrete ejectile energies to average energies. We use a modified ALICE code⁵ to obtain $\bar{E}_\gamma$. Although Kalbach gives an approximate value of k (0.04), we determined values more appropriate to our needs from our highest-energy data (40 MeV): $k = 0.0334$ for the (p,n) data and $k = 0.0462$ for the (d,2n) data. (Because we need the distribution of ions rather than ejectiles, we use $-a$.)

Figure 3 shows the angular distributions that fit the (p,n) data. The average energy of neutrons emitted for the 26-MeV case was 13.16 MeV. Fortunately, experimental angular distribution data are available for the $^{89}\text{Y}(p,n)^{89}\text{Zr}$ reaction obtained by other workers⁶ at LLNL. Their double-differential angular distributions were averaged over the emission of 12.64- to 13.67-MeV neutrons. It was necessary, for our purposes, to remove structure from the distributions to obtain the smoothed result that is shown and compared with our 26-MeV results in Fig. 4. We believe the comparison is close enough to lend credence to our procedure. We note that, for the 26-MeV data, $f_{\text{MSD}} = 0.8$. This number is in good agreement with our quantum-mechanical calculation of the direct part of the reaction published earlier.⁷

In Fig. 3, we have set $f_{\text{MSD}} = 1$ at 40 MeV, where we expect only direct reactions. Below 15 MeV, we expect that the excited nucleus

should be all compound, and here, $f_{\text{MSD}} = 0$. We also show the average parallel momentum of the ions in the CM system in Fig. 3. Only

Figure 3. Representative angular distributions for the data of Fig. 1. The numbers in parentheses are (f_{MSD}, a) .

Figure 4. The 26-MeV angular distribution derived during the fit to our $^{89}\text{Y}(p,n)^{89}\text{Zr}$ data compared with experimental data of Scobel and coworkers⁶ obtained for 12.64- to 13.67-MeV emitted neutrons. Our results correspond to $E_n = 13.16$ MeV.

qualitative significance is attached to these results.

In working up the (p,n) data, we made a small correction to the nuclear part of the LSS theory to improve the fit in the straight section of the range-energy curve. Here, there is every reason to expect full momentum transfer. In applying the LSS theory to the (d,2n) data, we made the same correction. (For chromium, the same correction was needed; but for titanium, no correction was needed.) Again, we assumed $f_{\text{MSD}} = 1$ at 40 MeV. We determined k and then proceeded to find the f_{MSD} required to fit the data at the lower energies.

Typical angular distributions that were generated are shown in Fig. 5. Even at low energies, we do not

obtain an isotropic CM distribution (i.e., a distribution constant with changing θ). Indeed, the results for isotropy, as shown in Fig. 2, are well above the straight-line section of the range-energy curve. We note that f_{MSD} is constant at 0.4 for $E_{\text{lab}} < 22$ MeV. This we consider a manifestation of deuteron breakup in the entrance channel of the reaction, an effect that we have studied in some detail using chromium data.^{8,9} With the neutron flying off as a result of Coulomb breakup without direct nuclear interaction, full momentum transfer does not occur.

Additional Studies

We have applied the formalism to both our chromium and titanium data with about the same level of

success. In addition, we have examined the results from tritons on titanium. Most significant is the fact that the (t, α) and (t, α n) reactions produce range-energy curves well below that expected for a compound nucleus, suggesting, with high probability, that these are pick-up reactions.

Acknowledgment

Special thanks go to M. Blann for modifying a version of his ALICE code to provide E_γ .

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Figure 5. Representative angular distributions for the $^{89}\text{Y}(d,2n)^{89}\text{Zr}$ data of Fig. 2. The numbers in parentheses are (f_{MSD}, a) .

Weapons Supporting Research

Silicon and Magnesium Emission from ^{238}Pu

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Hheavy-fragment emission by barrier penetration is a two-body decay process of a heavy nucleus into a fragment with $Z > 2$ and a nearly magic residual nucleus. Four nuclides (^{222}Ra , ^{223}Ra , ^{224}Ra , and ^{226}Ra) are known¹⁻³ to decay by emission of ^{14}C ; four nuclides (^{230}Th , ^{231}Pa , ^{232}U , and ^{233}U) are known⁴⁻⁷ to emit neon ions but no other intermediate-mass species; ^{234}U is known⁸ to emit both neon and magnesium ions (as well as alpha particles and spontaneous-fission fragments). The rough rule of thumb, that the most favorable parent for emission of a particular fragment is one leading to a heavy daughter close to doubly magic ^{208}Pb , dictates that emitters of silicon ions and heavier fragments will be transuranic nuclides.

We decided to search for heavy-fragment emission from ^{238}Pu because of the possibility that the results would help to discriminate among competing models of heavy-fragment radioactivity. The models fall into two distinct types: the unified models, where heavy-fragment emission is treated as a very asymmetric spontaneous fission with a well-defined final state; and the cluster models, which require the preformation of the heavy fragment inside the parent nucleus prior to its emission by tunneling through a potential barrier. Representative models of both types successfully predicted the rates of neon- and

magnesium-ion emission from ^{234}U (Ref. 8). Several other models of both types were unsuccessful in reproducing the experimental results. For heavy-ion emission from ^{238}Pu , there is no uniform prediction from a given type of model. Both a cluster model⁹ and a unified model¹⁰ predict approximately equal rates for magnesium- and silicon-ion emission from ^{238}Pu ; however, two different unified-model calculations predict a preponderance of either magnesium-ion¹¹ or silicon-ion decays.¹²

Experimental

The experimental difficulties in searching for decay modes involving emission of silicon ions or heavier fragments are twofold: according to most models, the branching ratio relative to alpha decay is expected to be below 10^{-15} , and the branching ratio relative to spontaneous fission decreases with Z^2/A and is expected to be below 10^{-7} for most even-even nuclides. To identify one fragment with $Z = 14$ and approximately 80-MeV kinetic energy out of more than 10^7 fission fragments with similar energies is a formidable experimental challenge. To deal with the high fission-fragment background, we exploited the fact that the range of any monoenergetic silicon ions emitted from ^{238}Pu is nearly twice that of the spontaneous-fission fragments.

Our approach was to expose LG750 phosphate-glass track

detectors, covered with a thin (13- μm) layer of aluminum foil, to a large-area source containing 10 mg of ^{238}Pu . The aluminum foil was thick enough to degrade the energy of the fission fragments to the point where they would not interact with the glass, but was thin enough not to stop the heavy ions. The interactions of alpha particles (which also penetrate the aluminum foil) with the glass do not produce tracks, but the intense flux does change the track-recording properties of the detectors. Accelerator calibrations were used to determine the effect of radiation damage on the glass and the response of the glass to various heavy ions of different energies.

We mounted the source face upward in the bottom of a vacuum chamber and then covered it with a hemispherical dome composed of the aluminum-covered track detectors. After evacuating the chamber, we maintained it at less than 10 Torr throughout the 172-d exposure. During this time, the alpha fluence to the detectors was $1.02 \times 10^{14} \text{ cm}^{-2}$, and the fission-fragment fluence was $3.5 \times 10^5 \text{ cm}^{-2}$. At the end of the exposure, we removed the aluminum foil and decontaminated the glass plates. The total recovered detector area was 352 cm^2 .

We etched the glass detector plates with 48% hydrofluoric acid long enough to remove 3.7 μm of glass and subjected each plate to an automated microscopic examination

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by transmitted light with a 25 $\times$ objective microscope. Candidate events (typically 100 cm⁻²) were located in this fashion; we then examined each one by eye to eliminate tracks due to flaws in the glass or pin holes in the aluminum covering foils. After locating events by this technique we made acetate replicas of them. We then further etched the detector plates and repeated the scanning and replication process. From each acetate replica, we obtained two values for the etch rate of tracks in the glass (v_T) relative to the general etch rate of undamaged glass (v_G). We

Figure 1. Identification of fragments emitted from ^{238}Pu as magnesium or silicon ions based on etch-pit geometry. The curves are based on calibrations obtained with ^{28}Si , ^{24}Mg , and ^{20}Ne beams at the Lawrence Berkeley Laboratory's SuperHILAC. Fission-fragment etch pits yielded values in the area labeled FF.

derived this value from the diameter of the etch pit at a given depth; usually, we determined it at both the tip of the pit and at a point halfway to the residual surface of the glass. The value of v_T/v_G for a given track is characteristic of the ion that produced it.

Results

We show in Fig. 1 the results of measuring track geometry for the seven heavy-ion events that we observed in this experiment. We also show the smooth curves resulting from our accelerator calibration experiments and a shaded area labeled FF resulting from fission-fragment bombardment of small areas of glass that were accidentally uncovered during the exposure of the dome of track detectors. From measurements of each track taken from acetate replicas produced at different points in the etching process, we know that we observed five events with atomic number $Z = 14$ and two events with $Z = 12$. Resolution was not good enough to

permit determining the mass of the fragments. The number of events corresponds to partial half-lives of about 2×10^{18} y for magnesium-ion emission and about 6×10^{17} y for silicon-ion emission.

In Fig. 2, we show the etchable ranges of the seven events shown in Fig. 1. This is a function of the kinetic energies of the emitted ions. The bracket above the histogram indicates the residual range in the glass expected when we take into account the thickness of the finite source and the distribution of the zenith angles in the aluminum foils. A possible shift of about 1 μm between the calculated and measured range distribution may suggest a kinetic energy deficit of less than 5% due to fragment excitation, which would be much less than the 13 to 14% seen in normal fission.

Despite the limited statistics, it seems clear that the emission rates for silicon and magnesium ions are of comparable magnitude, inconsistent with some model predictions (e.g., Reis, 11 and 12). The unified model of Poenaru and coworkers¹⁰ and the cluster model of Blendowske and Walliser⁹ yield predictions that are in good agreement with our experimental results, in terms of both absolute rates and relative branching ratios for magnesium- and silicon-ion emissions. A simple square well plus Coulomb potential model,² with a radius parameter selected in 1985 to fit ^{14}C -emission rates from radium isotopes, was surprisingly successful in reproducing the experimental results, giving at least as good a fit to all data on the subsequently studied neon, magnesium, and silicon decays as is achieved by the more sophisticated unified and cluster models.

Figure 2. Measured residual ranges of magnesium and silicon fragments emitted from a 0.21-mg/cm² ^{238}Pu source, after passing through a 3.5-mg/cm² aluminum foil. The ranges expected from the decay Q value are indicated by the bracket.

Future Plans

The success of the range-filter technique in eliminating the fission background in the case of ^{238}Pu should spur the investigation of heavy-fragment radioactivity in a number of other spontaneously fissioning transuranic nuclides. Our current plans include searching for the emission of even heavier ions from a source containing several micrograms of ^{242}Cm .

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Spontaneous-Fission Properties of ^{252}No

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In our studies of the spontaneous-fission (SF) properties of very heavy nuclei, we have identified a distinct fission mode characterized by broadly symmetric mass distributions and total-fragment energies that are consistently close to 200 MeV.^{1,2} The single, symmetric peak in the mass distribution sets this fission mode apart from the two peaks commonly known from fission of the lighter actinides. To explain this new fission mode, we have suggested^{1,2} that its appearance is related to the dropping of the outer fission barrier to a point below the ground-state level of the fissioning nucleus, as depicted in Fig. 1 for $^{260}\text{[104]}$.

This proposal was based on several theoretical clues concerning static fission barriers. The one most relevant to our hypothesis is the determination that the outer peak of the double-humped barrier lies from 0.5 to 2 MeV lower in energy when asymmetric shapes are considered,

as compared with only symmetric ones.³⁻⁵ Assuming that the lowest potential-energy path is preferred and that asymmetric deformations persist to the scission point, then asymmetric mass division would be expected. This explanation would account for the asymmetric mass distributions found throughout the actinides; hence, the outer barrier is often referred to as an "asymmetric" barrier. On the other hand, at smaller deformations within the inner barrier, nuclear matter resists mass-asymmetric deformations; therefore, this barrier has been found to be lower for mass-symmetric shapes.⁶

Figure 1. Fission barriers calculated with single-particle corrections to the liquid-drop barrier. Note the decrease in the outer barrier with increasing Z and N and its drop below the ground state in $^{260}\text{[104]}$.⁷

Finally, both experimental SF half-lives and theory⁶⁻⁹ indicated the outer peak of the "double-humped" fission barrier was dropping in energy below the ground state for nuclides with $Z \geq 100$ and $N \geq 158$. These calculations also showed that, for nuclei with $Z \geq 106$, a minimum no longer existed between the two barriers. In effect, the outer fission barrier had disappeared. Our finding of a sudden transition from mass-asymmetric fission in ^{256}Fm to a low-energy, mass-symmetric form in ^{258}Fm was in agreement with these theoretical estimates. Indeed, this was sufficiently assuring to cause us to offer such an explanation for the low-energy, mass-symmetric fission mode we have observed from the SF of six very heavy nuclides.^{1,2}

Experimental

Because our suggested hypothesis was not firmly established, we considered other experimental tests that might further gauge its viability. Among the feasible experiments, an important test would come from exploring the fission properties of the nobelium isotopes with $N \leq 156$ to determine where the transition

from mass asymmetry to symmetry occurs. We could then see if this transition was in accord with calculations of potential-energy surfaces that show at what neutron number the second barrier drops below the ground state. Because we had found mass symmetry already in ^{258}No and ^{262}No , it was necessary to measure the SF properties of ^{252}No , ^{254}No , and ^{256}No . Although the SF properties of 2.3-s ^{252}No were roughly determined some time ago, we thought a repeat determination was needed for verification. Also, for the first and easiest of the three experiments, this experiment offered the best chance of testing a newly modified instrument that we expected to use in measuring the SF properties of all three nobelium isotopes.

Our measurements of the fragment mass and kinetic-energy distributions from the SF of ^{252}No were made by producing this isotope from the $^{244}\text{Cm}(^{12}\text{C},4n)$ reaction, transporting the recoil products by a helium jet containing a KCl aerosol to our multiple alpha detector (MAD) system,¹⁰ in which the products are deposited by the helium jet on thin plastic films located near the outer edge of a 44.5-cm-diam disk. This

disk is rotated in 6-deg steps at fixed time intervals by a stepping motor so as to center the plastic films between opposing pairs of surface-barrier detectors. Thirty-two detectors above and below the disk are situated on the same radius as the sources and measure the energy deposited by correlated fission fragments.

In the past, we have used this instrument to search for short-lived alpha emitters, but for this experiment, we modified the preamplifiers to reduce their gain in order to accommodate more-energetic fission pulses. All fission pulse heights were digitized by computer-automated measurement and control (CAMAC) analog-to-digital converters and stored, together with the clock time of their appearance, by our computer. The disk, with 60 plastic films evenly spaced around its circumference, was indexed to sequential counting stations every 4.0 s, taking an average of 0.22 s to do so.

Results and Discussion

We measured an efficiency of 67% for the transfer of ^{246}Cf to our MAD system by the helium jet. However, this nuclide, which is

Figure 2. Half-life of ^{252}No obtained from our measurements of its spontaneous-fission properties.

Figure 3. Provisional mass distribution obtained from correlated fragment energies from the spontaneous fission of ^{252}No .

Figure 4. Post-neutron TKE distribution of the fragments from the spontaneous fission of ^{252}No .

produced by transfer reactions, has longer recoil ranges than does ^{252}No , which is made by a complete fusion reaction. We estimate, from our effective cross section of 80 nb and the absolute formation cross section of 250 nb obtained by Sikkeland and coworkers,¹¹ that our efficiency for the helium-jet transport of ^{252}No was about 35%, a value approximately equal to other helium-jet transport efficiencies we have determined from ^{12}C -fusion reactions. The ^{12}C -ion energy of 72.7 MeV was the same in both instances. We found a half-life of 2.44 ± 0.12 s for the observed SF activity (Fig. 2). This half-life is in excellent agreement with the total half-life of 2.30 ± 0.22 s obtained by measuring independently the decay of ^{252}No by both the α and SF modes.¹² Spontaneous-fission decay constitutes a 27% fraction of the total ^{252}No disintegrations.

Overall, we obtained 1741 correlated fission events, which can be compared with 154 events found by Bemis and coworkers¹² and with the 178 uncorrelated fissions found by Lazarev and coworkers.¹³ The latter investigators speculated that the mass division might be asymmetric, but this cannot be determined from uncorrelated fragment energies. However, the Bemis results clearly show mass asymmetry. We observed no long-lived fission activities in the detectors located between 156 and 180 deg from the jet-collection station. More than 100 s of decay had occurred before a sample reached these detector positions. In addition, the formation reaction that we chose for making ^{252}No was incapable of producing 2.6-h ^{256}Fm , a common contributor to a longer-lived SF background.

Our mass and total-kinetic-energy (TKE) distributions determined for the SF of ^{252}No are shown in Figs. 3 and 4, respectively. The mass distribution is asymmetric, with a shallow valley between peaks, not unlike that from the SF of ^{254}Fm and ^{256}Fm .

Our average post-neutron TKE of 194.3 MeV is also comparable to the values of 193.1 MeV for ^{254}Fm and 195.9 MeV for ^{256}Fm . The TKE noted for ^{252}No in the earlier study by Bemis and coworkers is larger than ours by some 8 MeV. All but about 2 MeV of this difference, however, can be accounted for by the fact that they made corrections for neutron evaporation and used a TKE of 183.1 MeV in the energy calibrations of their detectors with ^{252}Cf rather than the most recent parameters, which give the value of 181 MeV that we used here.¹⁴ Thus, our results for the fission properties of ^{252}No confirm the general features found in their investigation.

Conclusion

Not unexpectedly, we conclude from our asymmetric mass distribution that the second or "asymmetric" barrier is present in ^{252}No and that it will be necessary to look for the signature of its disappearance by determining the mass and TKE distributions from the SF of ^{254}No and ^{256}No . Such measurements for ^{254}No are being made, and we shall report those results next year.

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Electrochemical and Related Thermodynamic Properties of Nobelium

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Among the 30 elements of the lanthanide and actinide series, nobelium is the only element with a stable divalent state in aqueous solution¹ and is the next-to-last member of the actinide series, for which thermodynamic data are difficult to obtain. Therefore, knowledge of the physicochemical properties of nobelium is particularly useful for measuring and understanding systematic trends in the actinides and for predicting the chemical properties of even heavier elements.

Because weighable amounts of the heavy actinides are not available, direct measurement of many thermodynamic properties either is not possible or must be done by using traditional techniques modified for use with radionuclides. We previously reported measurements of the amalgamation potential in the presence of both weak (acetate) and strong (citrate)² complexing agents obtained by using the radiocoulometric method^{3,4} in which the aqueous and mercury phases are analyzed for radioactivity in lieu of the usual time-current measurement. We used the nuclide ²⁵⁹No ($t_{1/2} = 58$ m), which was produced at a rate of several hundred atoms per experiment at the Lawrence Berkeley Laboratory's 88-in. cyclotron by the use of the reaction ²⁴⁸Cm + ¹⁸O. We performed a series of bombardments, after which we chemically isolated a nobelium fraction for the radiocoulometry experiments.

In this article, we slightly revise our original results for the half-wave potentials, based on a re-examination of the raw data.⁵ Using our measurements, together with previous measurements and estimated properties for nobelium, we can deduce the potentials for both the No²⁺/No and No³⁺/No reaction couples and provide more accurate estimates of the standard heat and free energies of formation (ΔH_f° and ΔG_f°) and the other thermodynamic properties of No²⁺ and No³⁺ ions.

Results and Discussion

Electrochemical Properties.

We can use our revised half-wave potential (-1.47 ± 0.01 V) vs the standard hydrogen electrode, together with an estimate of the amalgamation energy, to derive the standard redox potential. Using a metallic radius of 1.97 Å, based on the observed variations with Z of the divalent metallic metals⁶ and the relationship between amalgamation energy and metallic radius for the alkaline earth elements,⁷ we estimate an amalgamation energy of 1.02 ± 0.05 V for nobelium. Therefore, the half-wave potential of the No²⁺/No couple is -2.49 ± 0.06 V. We then calculate a redox potential for the 3/0 couple of -1.18 V from our 2→0 measurement and from the measured 3→2 redox potential of 1.45 V.⁸ We can compare our results for the 2→0 potential with the estimate of Bratsch and

Lagowski (-2.47 V).⁹ Similarly, our deduced value for the 3→0 potential of -1.18 V can be compared with their prediction of -1.21 V (Ref. 9).

Thermodynamic Properties. We have calculated the free energies of formation for the No²⁺/No and No³⁺/No couples from the above potentials. We also estimate and summarize other thermodynamic properties of nobelium and compare the results to those in recent reviews of actinide properties.^{6,9,10} David^{6,10} uses an approach based on the systematic behavior of the 4f and 5f elements and ionic models, and Bratsch and Lagowski⁹ use a modified ionic model applied to thermodynamic measurements. Our results and the estimates we used in our calculations are summarized in Table 1.

Using $\Delta G_f^\circ = -nFE$, where n is the number of electrons transferred and F is the Faraday constant, we calculate a free energy of formation for No²⁺: $\Delta G_f^\circ(\text{No}^{2+}) = -480$ kJ mol⁻¹, directly from our half-wave potential (E) measurement for No²⁺→No in a noncomplexing medium. Similarly, we calculate $\Delta G_f^\circ(\text{No}^{3+}) = -342$ kJ mol⁻¹ from the above value for the No³⁺→No half-wave potential. An estimate of -477 kJ mol⁻¹ was made for $\Delta G_f^\circ(\text{No}^{2+})$ by Bratsch and Lagowski. Their estimate for No³⁺ was -350 kJ mol⁻¹.

From our calculated ΔG_f° values and from estimates of the entropy change, ΔS_f° , we calculate the heat of formation, ΔH_f° , for the 2⁺ and 3⁺ ions

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using $\Delta G = \Delta H - T\Delta S$. To estimate ΔS_f for the reaction $\text{No} + 2\text{H}_{\text{aq}} = \text{No}^{2+} + \text{H}_2$, we subtract the entropy of the metal, $S^0(\text{M})$, from the estimated entropy for aqueous No^{2+} , $S^0(\text{No}^{2+}, \text{aq})$, and the entropy for H_2 . Similarly for No^{3+} , $\Delta S_f = S^0(\text{No}^{3+}, \text{aq}) - S^0(\text{M}) + 3/2 S^0(\text{H}_2)$, where $S^0(\text{H}_2) = 131 \text{ J mol}^{-1} \text{ K}^{-1}$.

Before calculating ΔH_f , we need estimates for the above entropy terms $S^0(\text{M})$, $S^0(\text{No}^{2+}, \text{aq})$, and $S^0(\text{No}^{3+}, \text{aq})$. $S^0(\text{M})$ was estimated to be $65 \text{ J mol}^{-1} \text{ K}^{-1}$ in Ref. 7 and $66 \text{ J mol}^{-1} \text{ K}^{-1}$ in Ref. 9. Both references calculated $S^0(\text{M})$ using the method of Ward and Hill,¹¹ which correlated $S^0(\text{M})$ with atomic weight, with a calculated magnetic entropy term, and with the metallic radius. We used David's¹⁰ values of -27 and $-231 \text{ J mol}^{-1} \text{ K}^{-1}$ for $S^0(\text{No}^{2+}, \text{aq})$ and $S^0(\text{No}^{3+}, \text{aq})$, respectively. Ion entropies are usually estimated by summing an electronic term due to the degeneracy of the ground state with a term depending on the mass and radius of the ion. David derived a corrected entropy term, S_c , that depends on the structure of the aquo ion.⁶ He estimated S_c for divalent and trivalent ions⁶ from experimental values for alkaline-earths and trivalent lanthanide ions. Thus, S^0 is calculated by adding the correction term S_c to the electronic and mass entropy terms. From these entropy estimates, we calculated $\Delta S_f(\text{No}^{2+}, \text{aq}) = 39$ and $\Delta S_f(\text{No}^{3+}, \text{aq}) = -100 \text{ J mol}^{-1} \text{ K}^{-1}$. Using these ΔS values and our measured ΔG values, we calculate $\Delta H_f(\text{No}^{2+}) = -469$ and $\Delta H_f(\text{No}^{3+}) = -372 \text{ kJ mol}^{-1}$.

We also estimate the enthalpy of hydration for the di- and trivalent nobelium ions. The enthalpy of hydration can be calculated from the crystallographic radius and the coordination number by using a

semi-empirical analytical expression.¹² This expression is accurate to 1% for spherical ions of charge -1 to $+4$.

A crystallographic radius of $1.05 \text{ \AA}$ for No^{2+} was estimated from experimental measurements of the ion exchange and liquid-liquid extraction behavior of nobelium vs the alkaline earth elements.¹³ There are no analogous ionic radius measurements for No^{3+} . David¹⁰ estimated a crystallographic radius for No^{3+} of $0.90 \text{ \AA}$ for coordination number 6 and $1.02 \text{ \AA}$ for coordination number 8 by comparing the iso-electronic ions in the 4f and 5f series. David and coworkers¹² obtained an identical value by considering the difference, D , between the trivalent radii of actinide and lanthanide homologs; D was assumed to be $0.033 \text{ \AA}$ from einsteinium to lawrencium, as it is observed experimentally from americium to californium. Recent determinations of the Md^{3+} and Lr^{3+} radii from aqueous chromatography^{14,15} results allow a more direct evaluation. On the basis of the very close elution positions of mendelevium and lawrencium,

these authors estimated a $0.015\text{-}\text{\AA}$ difference in the radii. This difference should be compared with the homologous lanthanide ions Tm^{3+} and Lu^{3+} . Templeton and Dauben¹⁶ estimated a difference of $0.021 \text{ \AA}$. However, Shannon¹⁷ estimated $0.019 \text{ \AA}$ from a set of radii that are consistent with valence, coordination number, and radius. By analyzing new crystallographic data from several isostructural series of compounds with Shannon's radii, a difference of $0.016 \text{ \AA}$ was obtained.¹⁰ Thus, we conclude that the proposed nobelium radii (Table 1) are consistent with the experimental data if we use Shannon's approach.

We adopted a coordination number in the primary sphere of $N = 6$ and 8 for the divalent and trivalent nobelium ions, respectively, based on correlations of the crystallographic radii with elution chromatographic behavior of the divalent and trivalent lanthanide and actinide ions.¹² Using the above crystallographic radii and coordination numbers, we calculate $\Delta H_h(\text{No}^{2+}) = -1606$ and $\Delta H_h(\text{No}^{3+}) = -3685 \text{ kJ mol}^{-1}$, respectively.

Table 1. A summary of measured and estimated thermodynamic properties for No, No^{2+} , and No^{3+} .

	No (metal)	No^{2+}	No^{3+}
$R (\text{\AA})$	1.97 ^a	1.05 ^b 1.02 ^{b,d}	0.90 ^{b,c}
$S^0 (\text{J mol}^{-1} \text{ K}^{-1})$	65 ^a	-27 ^b	-231 ^b
$\Delta H_s (\text{kJ mol}^{-1})$	126 ^a		
$\Delta H_h (\text{kJ mol}^{-1})$		-1606 ^b	-3685 ^b , -3753 ^e
$\Delta G_f (\text{kJ mol}^{-1})$		-480 ^f	-342 ^f
$\Delta H_f (\text{kJ mol}^{-1})$		-469 ^f	-372 ^f

^a Ref. 6.

^b Ref. 7.

^c Coordination number = 6.

^d Coordination number = 8.

^e Ref. 21.

^f This work.

To complete our summary, we include the enthalpy of sublimation, ΔH_s , which was estimated to be $126 \pm 8 \text{ kJ mol}^{-1}$ for divalent nobelium metal⁶ by using correlations between the actinide and rare earth elements.^{18,19}

Conclusion

In conclusion, nobelium is the last member of the actinide series (and of the periodic table) for which electrochemical measurements have been made. From the systematic behavior of the f-series elements, we have estimated some standard thermodynamic values for nobelium. Since two long-lived lawrencium nuclides, ^{261}Lr ($t_{1/2} = 39 \text{ m}$) and ^{262}Lr ($t_{1/2} = 216 \text{ m}$), were recently discovered,²⁰ it is now possible to extend electrochemical measurements to the last member of the actinide series. However, it appears unlikely that any elements heavier than lawrencium will have half-lives long enough to permit electrochemical measurements.

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Status of the Experiment to Measure the Mass of the Electron Antineutrino

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The mass of the neutrino is an important parameter in many areas of physics. For example, a neutrino mass of even a few electron volts would have a profound influence on cosmology because of the vast number of neutrinos in the universe. Also, because modern theories of particle physics allow neutrinos to have a nonzero mass, the discovery of such a mass would give some proof of the correctness of these theories and would help fix the values of some of the parameters.

The mass of the electron antineutrino can be determined by carefully measuring the beta decay of tritium: a nonzero neutrino mass would alter the shape of the electron spectrum near the endpoint energy of the beta-decay process. To date, the results of tritium beta-decay experiments have produced conflicting claims. For example, a group at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow claimed¹ to have evidence for an electron antineutrino mass between 18 and 45 eV. However, groups in Switzerland,² Tokyo,³ and Los Alamos⁴ who also measured the beta-decay of tritium found no evidence for a neutrino mass with upper limits as low as 18 eV.

Our experiment was designed to eliminate the systematic errors encountered in the other attempts to make this measurement. Briefly:

- We use a cryogenic, gaseous atomic-tritium source, rather than a source with tritium embedded in a solid as is used by other experimenters. Electrons from tritium atoms that decay in our source are guided into a large, toroidal-field

spectrometer by a system of five solenoidal superconducting magnets. Only electrons emitted from the gaseous atomic tritium are visible to the high-resolution spectrometer.

- The spectrometer (Fig. 1) focuses the electrons onto a cylindrical, silicon detector that is segmented into 16 independent, ring-shaped elements. Each element has its own

amplifier system. Because the silicon detector has good energy resolution, we can distinguish between good events and background from radioactive decays and secondary cosmic-ray interactions. We operate the spectrometer at constant field and current settings to avoid subjecting the spectrometer to thermal stress. To obtain the energy

Figure 1. Front view of the toroidal field spectrometer. Large ring is 6.5 ft in diameter.

spectrum of the electrons, we use a variable electric potential to accelerate the electrons emitted in the source.

A more detailed description of the source and toroidal-field spectrometer can be found in Ref. 5.

The effect of any neutrino mass on the beta-decay function will be smeared out by the finite width of the resolution function of the measuring system; therefore, this resolution must be unfolded from the raw data to extract the neutrino mass. An important aspect of our experiment is our ability to measure our system's resolution function with high accuracy using $^{83\text{m}}\text{Kr}$. This isomeric state is produced by the electron-capture decay of ^{83}Rb ($t_{1/2} = 86$ d). The isomer, which has a half-life of 1.8 h, decays by a cascade of two electromagnetic transitions with energies of 32 and 9.4 keV. The 32-keV E3 transition has a total conversion coefficient of about 2000; the K-conversion line carries about a

fourth of this intensity and has an energy of 17.8 keV. Therefore, the krypton source gives us an electron line for calibration in the region of interest in the tritium-decay spectrum. Also, since krypton is a noble gas, the calibration electrons come from the same environment as will the tritium in the final experiment.

Status

During the past year, we concentrated on optimizing the performance of the apparatus.

- We extensively leak-checked the source tube that will hold the gaseous tritium and achieved a vacuum of better than 5×10^{-9} Torr.
- The temperature-control system is fully operational: we heated the tube to 150°C to improve the vacuum, and we also cooled the tube to 20 K to simulate the expected measuring conditions. We found that a source-tube temperature of 100 K maximizes the observed count rate of the krypton gaseous source; i.e.,

the krypton in the source tube moves more slowly than the krypton in the return lines, thereby increasing the chance of decay in the region visible to our spectrometer.

- The high-voltage insulation tests on the entire source assembly were successful to 20 kV, and with minor modifications, the source could be run as high as 30 kV.

- The five superconducting magnets have been slightly modified to optimize their performance. We strengthened the support system for the coil-formers of each of the magnets and aligned them to our source tube. In addition, we changed the thermal insulation of the magnets to decrease their liquid-helium consumption. The two long cryostats now each boil off 9.5 l/d of helium, and the three short magnets boil off 5.5 l/d, a rate that requires the reservoirs to be refilled every 5 d. All of the magnets have produced stable fields of more than 1 T, which is sufficient for our experiment.

We used ^{83}Kr to demonstrate the ability of our magnet system to guide beta-decay electrons from the gaseous source into the electron spectrometer. Figure 2 shows the spectrum of electrons resulting from this test as recorded by our Si(Li) monitor detector positioned in front of the toroidal-field spectrometer. For this spectrum, the source table is at a potential of -12 kV. The K, L, and M lines of the 32-keV transition as well as the L and M lines of the 9-keV transition are clearly visible. The figure shows that only electrons are visible to the detector, since there are no x-ray peaks in the spectrum.

To demonstrate magnetic-mirror effects at both ends of the source, we measured the ^{83}Kr spectrum with a small surface-barrier detector at the far end of the source. This detector saw a 45% increase in rate when we

Figure 2. The electron spectrum of $^{83\text{m}}\text{Kr}$ from the gaseous source as recorded in the Si(Li) monitor detector. The source table was at an acceleration voltage of 12 kV.

decreased the field in the magnet positioned farthest from the spectrometer. This increase occurred because we no longer reflected these electrons back down the source tube. We also observed no count rate in this small detector when the field in that same magnet was set to zero. In a similar manner, we observed an even larger count rate at this end of the source by creating a magnetic mirror in the magnet closest to the spectrometer.

We also began verifying the performance of the toroidal-field electron spectrometer. For the first tests, we used an electron gun to tune the compensation coils, to optimize the positions of the first slit and the detector, and to study the focusing power of the electrostatic deflection plates. The electron gun consisted of a 1-cm-diam stainless-steel sphere mounted on a high-voltage feedthrough. The sphere was electroplated with a thin coating of platinum. A beam of ultraviolet light (254 nm) from a mercury lamp created 20-meV electrons from the platinum; these electrons were then accelerated to the voltage we produced with our high-voltage power supply. The result was a tunable, monochromatic electron beam of high intensity that could be installed inside our large vacuum tank. We isolated the effects of each set of the electrostatic elements by using the detector diagnostic cup. This motor-driven cup contains a slit that allows only a narrow angular range of electrons to impinge on the detector. Using these methods, we achieved a resolution of 7 eV for 22-keV electrons.

A more rigorous verification of our system's performance is given by measuring the decay of $^{83\text{m}}\text{Kr}$. The tuning described above was repeated to correct for the different

Figure 3. The K-conversion electron line of the 32-keV transition in $^{83\text{m}}\text{Kr}$. The toroidal-field spectrometer was set to analyze 18-keV electrons. The resolution is 8 eV (FWHM). The inset graph shows the shake-off tail plotted on a log scale. These data were collected in 4 h.

Figure 4. The L-conversion electron lines of the 32-keV transition in $^{83\text{m}}\text{Kr}$. The toroidal-field spectrometer was set to analyze 18-keV electrons, i.e., the L electrons were decelerated to this energy.

source geometry and for the effects of the superconducting magnets. The results for the K-conversion line for the 32-keV transition are shown in Fig. 3. These data were obtained with the spectrometer set to analyze 18-keV electrons. The spectrum shows the main Gaussian resolution peak with a full width at half maximum (FWHM) of 8 eV. The low-energy tail is caused by rearrangement of atomic electrons (shake-up and shake-off electrons). The important point is the clear separation of these two components. This separation allows us to determine our machine's resolution without having a precise knowledge of the atomic effects associated with the K-conversion process in krypton. Figure 4 shows the L-shell

conversion electron spectrum of the 32-keV transition. The extracted L2/L3 ratio of 0.61 ± 0.02 is in good agreement with the theoretical value for a pure E3 transition.

In the next year, we plan to apply additional ^{83}Kr studies to the further optimization of our machine. We hope to have our first results on tritium before the end of 1990. At this time, we have encountered no problem that would keep us from being sensitive to a neutrino mass greater than 5 eV.

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Coriolis Coupling in the Rotational Bands of Deformed Odd-Odd Nuclei

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It is now well recognized that the Coriolis force plays an important role in influencing the structure of deformed nuclei at both low and high spins. Although many Coriolis band-mixing calculations have been carried out in the past for rotational bands in odd-odd nuclei, these calculations have been limited in scope. Usually, the mixing of only two or three known bands was considered. In fact, it has generally been thought that odd-odd nuclei should have more exact rotational energy systematics because of the experimentally

observed large moments of inertia and decreased pairing.¹ However, recent high-spin data for the $K = 2^+$ and 4^- bands in ^{182}Re exhibit a high degree of distortion.² This focused our attention on questions of the degree and the extent to which Coriolis distortion is present in rotational bands of odd-odd nuclei.

An examination of the experimental data revealed that practically all $K^- \equiv |k_p - k_n|$ bands exhibit an odd-even staggering. Of the 43 K^- bands where staggering is observed, 25 are $K = 1$ bands, and the rest are

$K = 2, 3$, or 4 bands. The origin of the odd-even staggering in the $K = 1$ bands can immediately be traced to direct Coriolis coupling with Newby-shifted $K = 0$ bands. Therefore, it seems likely that the staggering in the $K = 2, 3$, and 4 bands is the result of higher-order Coriolis coupling with $K = 0$ bands.

In Fig. 1 we summarize the empirical evidence for odd-even staggering in the rotational bands of four nuclei in the rare-earth region: ^{168}Tm , ^{176}Lu , ^{182}Ta , and ^{182}Re . The first three were chosen because a

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large amount of experimental data is available for each nucleus. The nucleus ^{182}Re was chosen because a $K = 2^+$ band and a $K = 4^-$ band in this nucleus exhibit significant amounts of staggering, which is somewhat unusual for bands with $K > 1$. In this figure, we plot the ratio $\Delta E(l \rightarrow l-1)/2l$ vs $2l^2$ for all K^- bands where experimental data are available (except for $K = 0$ bands, which are already known to be staggered as a consequence of the residual neutron-proton interaction). One expects linear behavior in such a plot if a rotational band behaves according to the usual $l(l+1)$ formula. It can be seen that the magnitude of the staggering is quite variable, ranging from strong fluctuations to only a minor effect.

Calculations

In our calculations, we have used a model of two quasi-particles plus a rotor³ to describe the low-lying energy spectra of deformed odd-odd nuclei. Because the model is well known, we discuss it only briefly. The Hamiltonian used in this model includes the usual elements that describe the energies of intrinsic single-particle states, rotational motion, rotation-particle coupling, particle-particle coupling, and a residual n-p interaction. The total Hamiltonian matrix was diagonalized for each value of angular momentum.

To perform a Coriolis-coupling calculation in as complete a fashion as is practical, we often must consider the mixing of several bands representing the various two quasi-particle states that are interacting strongly. Because such calculations can involve a large number of parameters, it is most appropriate to select nuclei in which many bands have been characterized experimentally. Even then, it is often necessary to estimate the energies of certain unidentified bands; e.g., the crucial

$K = 0$ bands, whose odd-even staggering can be transmitted to the higher K bands through Coriolis coupling. Therefore, we obtained estimates for the excitation energies of unidentified bands by use of a simple, semi-empirical formulation⁴⁻⁷ that employs the known properties (excitation energy and rotational parameter) of given quasi-particle states in neighboring odd- A nuclei.

The calculations are performed by fitting all of the experimentally known levels in the rotational bands in question. Variable parameters include the band energies and rotational parameters for the experimental levels. The $\langle j_+ \rangle$ matrix elements were calculated by the use of Nilsson wave functions.⁸ The most essential of the matrix elements were also treated as free parameters and were adjusted in the fitting procedure. Another important class of free parameters was the Newby shifts for the $K = 0$ bands included in the calculation.

We have carried out Coriolis-coupling calculations for the four nuclei shown in Fig. 1. Generally, we have succeeded in making precise fits to the levels of rotational bands in these nuclei, even when the bands exhibit significant staggering. For $K = 1$ bands, the magnitude of the observed staggering is a function of the following factors: (1) the Nilsson orbitals occupied by the unpaired nucleons and, hence, the magnitudes of the $\langle j_+ \rangle$ matrix elements connecting $K = 0$ and 1 bands; (2) the magnitude of the Newby shift in an interacting $K = 0$ band, which is also determined by the Nilsson orbitals of the unpaired nucleons; (3) the energy difference between interacting levels; and (4) the number of $K = 0$ bands interacting with the $K = 1$ band in question.

For bands with $K > 1$, the observed staggering has been transmitted by means of mixing with $K = 0$ and 1 bands. Thus, staggering in the higher- K bands is most likely to be found among orbitals that

Figure 1. Calculated (dotted lines) and experimental (solid lines) data for K^- bands in four odd-odd nuclei.

couple strongly by means of Coriolis mixing; i.e., those with high j values such as the configurations arising from the $h_{11/2}$, $i_{13/2}$, and $j_{15/2}$ spherical orbitals. We also find that terms of the particle-particle-coupling type can be important in some cases and may lead to significant admixtures in the wave functions.

Among the bands shown in Fig. 1, the $4^-[(1/2)[541]_p - (9/2)[624]_n]$ band in ^{182}Re is of particular interest. The nine experimentally determined levels in this band were fitted in a calculation that included 12 rotational bands, six in the $K^+[(1/2)[541]_p + [i_{13/2}]_n]$ series and six in the $K^-[(1/2)[541]_p - [i_{13/2}]_n]$ series. The odd-even staggering observed in the 4^- band is the product of the Newby shift in a $0^-[(1/2)[541]_p - (1/2)[660]_n]$ band with an estimated excitation energy of 2000 keV. Since this band has $k_p = k_n = 1/2$, its Newby shift will include contributions both from the usual matrix element and from a term of the form of $a_p \times a_n \times h^2/2\theta$. The latter quantity is estimated to be between 200 and 250 keV, much larger than the usual E_N matrix element.

Although we cannot provide a full discussion of these results here, it should be noted that the odd-even shift of this $K = 0$ band is transmitted to the 4^- band level by means of Coriolis mixing in both the K^- and K^+ series. Surprisingly, the more significant source of the odd-even staggering in the 4^- band appears to arise from its interaction with bands

in the K^+ series. These bands display an interesting property not found in the K^- series, namely, that the lower-lying bands in the series show odd-even staggering of one phase, and the higher-lying members of the series show odd-even staggering of the *opposite phase*.

Conclusion

We observe an odd-even staggering in most of the K^- bands of odd-odd rare-earth and actinide nuclei. To explain the staggering, which is observed in $K^- = 1, 2, 3$, and 4 bands, we have performed detailed Coriolis-mixing calculations that are nearly complete, in the sense that all the important bands with either known or estimated energies were taken into account. Successful reproduction of the odd-even staggering in four nuclei for which calculations were done implies that the odd-even staggering is indeed a result of Coriolis mixing.

Also, it has become clear from our study that K^- bands are more staggered than K^+ bands because the former can be coupled more directly to Newby-shifted $K = 0$ bands. The amount of staggering may be large or small, depending on a number of factors such as Nilsson orbitals occupied by the unpaired nucleons, the value of $\langle j_+ \rangle$, and the closeness and the number of interacting $K = 0$ bands. Further discussion of this work can be found in Ref. 9.

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Search for a Shape Isomer in ^{194}Hg Populated by ^{194}Tl Beta Decay

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Recent theoretical calculations (Weiss et al.,¹ Bonche et al.,² Girard et al.,³ Chasman⁴) predict that nuclei in the vicinity of ^{194}Hg should possess shape isomers analogous to the fission isomers identified in the actinide nuclei. However, because the fission barriers of these nuclei would be much higher than those of the actinide nuclei, the main decay mode of these shape isomers would be gamma-ray decay. Experience with the fission isomers suggests that the shape isomers would be weakly populated by nuclear reactions; thus, the gamma-ray decay mode would be difficult to identify. Nevertheless, successful observation of shape isomers outside the actinide region would be important because it would validate theoretical concepts of the nuclear potential energy surface and provide an opportunity to study nuclei at high deformation but low spin.

We have begun an experimental program to search for and characterize shape isomers in the mercury nuclei. As a part of this program, we are studying the beta decay of ^{194}Tl to levels in ^{194}Hg . Because the proposed shape isomer in ^{194}Hg is at about 4 MeV (Ref. 1) and the

Q_{β} value for ^{194}Tl is about 5.15 MeV, it is possible, from an energy standpoint, for ^{194}Tl decay to populate a ^{194}Hg shape isomer. The main objective of this experiment was to try to identify the E2 gamma-ray decay of the shape isomer to the first 2^+ level in ^{194}Hg . The second objective was to identify candidates for the lowest 1^- level in ^{194}Hg because we know from studies in the uranium nuclei that the main gamma-ray decay branch can be either an E2 transition to the lowest 2^+ level or an E1 transition to the lowest 1^- levels.^{5,6}

Two isomers are known in ^{194}Tl : a 2^- state with a half-life of 33.0 m and a (7^+) state with a half-life of 32.8 m (Ref. 7). The level systematics of these isomers in heavier thallium isotopes suggest that the 2^- state is the ground state of ^{194}Tl , with the (7^+) state lying several hundred kiloelectron volts higher. The Q_{β} value of ^{194}Tl is estimated to be 5.15 MeV. Amov and coworkers,⁸ using beta decay to study the structure of ^{194}Hg , identified the first 2^+ level at 428 keV and established additional levels populated by both the low-spin and high-spin isomers of ^{194}Tl . Akovali and coworkers^{9,10} observed the decay of

mainly the low-spin ^{194}Tl isomer. They did so by producing ^{194}Pb , which in turn decays to the 2^- isomer of ^{194}Tl and then to ^{194}Hg .

Experimental Procedure

We used the UNISOR online isotope separator at the Holifield Heavy Ion Research Facility (Oak Ridge National Laboratory) to produce the ^{194}Tl activity for this experiment. The production reaction was carbon on natural rhenium foils at a bombarding energy of 90 MeV. The separator deposited the activity on a tape, which moved it from the deposition site to two successive detector stations. Activity was collected for 180 s and transported within 3 s to the first detection station, where it was counted for 180 s. While it was being counted, the next sample was deposited.

The first detector station, where the data reported here were collected, consisted of two large, thin-window, high-purity, germanium detectors oriented facing each other. These detectors, with efficiencies of 40% and 23%, were as close to the deposited sample as the tape-transport apparatus would allow (about 2.5 cm). We placed an x-ray

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absorber package between the sample and the 40% detector to reduce summing.

After accumulating both gamma-ray singles and coincidence data, we stored three-parameter coincidence data (two gamma-ray energies and the time between the two gamma rays) on magnetic tape. We sorted the coincidence data offline into a two-dimensional energy matrix, with the requirement that the two gamma rays be within a prompt coincidence window of about 25 ns. We made projections from this two-dimensional array by gating on specific peaks and analyze the projected spectra with the gamma-ray fitting code, FITEK. Finally, we determined the energy and absolute efficiency for the data-accumulation system, using a calibrated ^{154}Eu source.

Data and Results

Comparison of the $2^+ \rightarrow 0^+$ and $5^- \rightarrow 4^+$ transition intensities indicates that about 80% of the ^{194}Tl activity produced in this experiment was a result of the decay of the (7^+) isomer. The high-spin isomer of ^{194}Tl could populate the proposed shape isomer indirectly by first populating the high-lying 6^+ and 8^+ levels, which belong to the rotational band built on the shape-isomeric 0^+ level and lie 200 to 350 keV above the shape isomer. These levels, in turn, would decay to the shape isomer if the barrier against their decay to lower-lying, less-deformed levels were sufficiently high.

The E2 decay mode for the shape isomer is expected to populate mainly the lowest 2^+ level at 428 keV because the E2 transition rate is proportional

to the transitional energy to the fifth power. We used the projected spectrum coincident with the 428-keV transition to obtain the intensity (in this case, an upper limit on the intensity) for a high-energy E2 transition out of the isomer. The absolute normalization for this intensity was made by using the known intensity of the 749-keV transition, which is coincident with the 428-keV transition. The 749-keV transition is emitted in 76% of the decays of ^{194}Tl (Ref. 8). Shown in Fig. 1 is the 3- to 4-MeV portion of the spectrum coincident with the 428-keV transition. The inset shows the 749-keV transition coincident with the 428-keV transition.

As is evident in Fig. 1, we observed no distinct gamma rays in the 3- to 4-MeV energy range. As a result, only an upper limit can be quoted on the intensity of a high-energy E2 transition from the shape isomer to the 2^+ level. This limit is determined by assuming that the upper limit to the photopeak area at any energy is proportional to the square root of the counts in an energy bin equivalent to the photopeak width at that energy. To suppress the channel-to-channel fluctuations in the number of counts, we

Figure 1. The spectrum of gamma rays in the 3- to 4-MeV energy range coincident with the 428-keV transition from the 2^+ level to the ^{194}Hg ground state. No individual gamma rays were observed. The upper limit for the intensity of a weak gamma ray is proportional to the square root of the spectrum at the energy of a possible gamma ray. The inset shows the 749-keV gamma ray, which is coincident with the 428-keV transition and is used for normalization purposes.

Figure 2. A 2σ upper limit for the intensity of an E2 gamma ray from the proposed shape isomer in ^{194}Hg to the 2^+ level at 428 keV. The intensity is expressed as a percent of the ^{194}Tl beta-decay intensity.

averaged the counts over 50-keV bins before calculating the limit for the photopeak width. The smooth curve in Fig. 2 approximates the 2σ upper limit determined in this way for the E2 decay branch for transition energies from 3 to 4.5 MeV, which correspond to isomer energies from 3.428 to 4.928 MeV. This limit ranges from about 0.022% for a 3-MeV transition to about 0.003% for a 4.5-MeV transition.

We offer two comments to help evaluate the sensitivity of this experiment. First, using coincidence gates, we projected spectra on the 735- and 749-keV gamma rays that depopulate the 6^+ and 5^- levels at 1799 and 1813 keV, respectively. These spectra

clearly show that high spin levels are populated by beta decay up to at least 4.2 MeV in ^{194}Hg . Preliminary estimates indicate that these levels are populated at least a factor of 10 more strongly than indicated by the limit noted in the preceding paragraph. Second, if we assume that the E2 gamma ray to the lowest 2^+ accounts for about a third of the depopulation of a proposed isomer (as it does in ^{238}U)⁵ and that population of the isomer proceeds through one level (a 6^+ level, for example), we can calculate the $\log ft$ value for that level. The $\log ft$ values obtained by using these assumptions are >8.0 for E2 transitions between 3 and 4 MeV. Ordinary allowed beta decay

could populate such levels with $\log ft$ values ≤ 5.2 . Thus, beta decay to the highly deformed states built on a shape isomer is hindered by μ to three orders of magnitude or more, compared with allowed beta decay.

We have also obtained preliminary information from this experiment on possible candidates for the lowest-lying 1^- level in ^{194}Hg . No low-lying 1^- levels have been identified previously in the mercury nuclei. In nearby platinum nuclei, they have been identified at about 1800 keV, which is about where we might expect them in the mercury nuclei. We have analyzed the coincidence data with the specific goal of identifying new low-spin levels below about

Figure 3. New low-lying, low-spin levels in ^{194}Hg from the coincidence data of this experiment. Levels at 1502, 1959.9, 1980.0, 2069.4, and 2105.9 keV are candidates for 1^- levels.

2.2 MeV and characterizing them as much as possible from these data.

We have identified 11 new levels below 2200 keV in ^{194}Hg (Fig. 3), of which five are potential candidates for 1^- levels: 1502, 1959.9, 1980.0, 2069.4, and 2105.9 keV. Other identified levels decay either to the lowest 4^+ level or to the positive-parity 1469.0-keV level, which most likely has a spin of 3 or 4. Additional experiments emphasizing the decay of the low-spin ^{194}Tl isomer, in conjunction with conversion-electron or angular distribution spectroscopy, will be necessary to fully characterize these levels and to definitely establish whether any of them has a spin and parity of 1^- .

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Possible Evidence for 4-Particle, 4-Hole Excitations in ^{146}Gd

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Production^{1,2} of the radioactive target ^{148}Gd has made it possible to study levels in the $Z = 64$ closed-subshell nucleus ^{146}Gd by the two-neutron pickup reaction $^{148}\text{Gd}(p,t)^{146}\text{Gd}$. This reaction is expected to populate the 0^+ ground state of ^{146}Gd in a particularly strong way by picking up the two neutrons outside the 82-neutron closed shell. However, by picking up two neutrons from the filled $N = 82$ shell, it is also expected to produce strong excitations of the 2-particle 2-hole (2p2h) neutron pairing-vibrational (pv) states. Figure 1 illustrates these processes in the simplest, good shell-

model picture (I) and in the more realistic case of some proton-pair scattering across the $Z = 64$ subshell gap (II). The 0^+ and 2^+ pv states have been observed³ to be strongly populated in the (p,t) reaction at 3.020 and 3.383 MeV, respectively.

The proton 2p2h states in ^{146}Gd occur at lower excitation energies than the neutron states because the energy gap at $Z = 64$ (2.0 to 2.5 MeV) is smaller than at $N = 82$. These states are not populated in the (p,t) reaction by the simple mechanism illustrated in Fig. 1 for the neutron states. However, pairing correlations across the $Z = 64$ gap will

cause some admixture of the proton 2p2h 0^+ state into the ground state of ^{148}Gd , enabling the 2p2h state to be weakly populated by two-neutron pickup reactions. This state occurs at 2.165 MeV of excitation, strongly populated by the $(\alpha,2n)$ reaction⁴ and weakly by (p,t).³

In their recent study of the $^{148}\text{Gd}(p,t)^{146}\text{Gd}$ reaction, Mann and coworkers⁵ found, in addition to the pv states discussed previously, a strongly populated 0^+ state at 4.534 MeV (Fig. 2). We suggest that this state may consist of a combined proton 2p2h, neutron 2p2h excitation in ^{146}Gd . Such a 4p4h excitation

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should have an intensity in the (p,t) reaction at least as high as that of the proton 2p2h state at 2.165 MeV.

Calculations

To make theoretical predictions about the excitation energy and the structure of this 4p4h state, we have performed calculations⁶ based on the following four-level model: (1) the 0^+ reference state (the unperturbed state consisting of a closed $N = 82$ shell and a closed subshell at $Z = 64$); (2) a proton 2p2h state; (3) a neutron 2p2h state; and (4) the proton 2p2h, neutron 2p2h (i.e., 4p4h) configuration. The model uses a short-range delta interaction that has been described earlier,^{7,8} with an effective strength of $V_{\text{eff}} = 400 \text{ MeV}\cdot\text{fm}$. Single-particle energies are from studies of the $N = 82$ isotones.^{9,10} The unperturbed energies of the 2p2h states were taken as 2.244 MeV (proton) and 3.500 MeV (neutron), based on the 2p and 2n

separation energies from the most recent mass tables¹¹ and with some adjustment from systematics. The unperturbed 4p4h energy was 3.889 MeV, obtained from the procedure described by Broglia and Bortignon.¹² This value remains essentially unmodified after corrections for the residual interactions.

To facilitate presenting the wave functions that result from the calculations, we use the following shorthand notation for the basis states: $|0\rangle$ for the 0^+ reference state, $|1\rangle$ for the proton 2p2h configuration, $|2\rangle$ for the neutron 2p2h configuration, and $|3\rangle$ for the 4p4h configuration. The calculated level energies and wave functions for the four 0^+ states are as follows:

$$0.00 \text{ MeV:} \\ 0.95|0\rangle + 0.22|1\rangle - 0.19|2\rangle - 0.06|3\rangle$$

$$2.39 \text{ MeV:} \\ -0.24|0\rangle + 0.90|1\rangle - 0.02|2\rangle - 0.36|3\rangle$$

$$3.55 \text{ MeV:}$$

$$0.13|0\rangle + 0.25|1\rangle + 0.83|2\rangle + 0.48|3\rangle$$

$$4.76 \text{ MeV:}$$

$$0.11|0\rangle - 0.27|1\rangle + 0.52|2\rangle - 0.80|3\rangle$$

Discussion

These results show that the energy of the 4p4h state is pushed up by almost 1 MeV above its unperturbed value, bringing it into the region of the observed 4.534-MeV 0^+ state. Also, the amplitudes of the $|2\rangle$ components in the neutron 2p2h and the 4p4h states give us a simple estimate of the relative cross sections for populating these states in the (p,t) reaction. This ratio is $(0.83/0.52)^2 = 2.55$, to be compared with the observed ratio⁵ of $229/91 = 2.5$ (Fig. 2). Similarly, the predicted ratio for populating the ground and the proton 2p2h states is $(0.95/0.24)^2 = 16$, in reasonable agreement with the observed value of 10.

Figure 1. Schematic of configurations that can be excited by the $^{148}\text{Gd}(p,t)^{146}\text{Gd}$ two-neutron pickup reaction. Possible final states are indicated on the right-hand side. The sharp, subshell occupation in (I) (left-hand side) represents the $Z = 64$ subshell closure, whereas the smooth pair distribution across the $Z = 64$ subshell closure (II) represents possible admixtures in the 0^+ ground state of ^{148}Gd .

Figure 2. Experimental cross sections (in μb) and excitation energies (keV) for selected 0^+ and 2^+ levels observed in the $^{148}\text{Gd}(p,t)^{146}\text{Gd}$ reaction.⁵ The "pv" indicates pairing-vibrational states for protons (p) or neutrons (n).

Finally, we expect 2^+ and higher excitations to be associated with this $4p4h$ configuration. An estimate of the excitation energy of the 2^+ state can be obtained from the known $4p4h$ band in ^{16}O by correcting the effective moment of inertia for the difference in masses. This gives an excitation energy of approximately 200 keV above the 0^+ state, or 4.73 MeV for the 2^+ state. As a first approximation, we expect the ratio of cross sections for populating the 2^+ and 0^+ $4p4h$ states to be equal to the ratio for populating the 2^+ and 0^+ states of the neutron $2p2h$ configuration. The strongly populated level at 4.726 MeV is a good candidate for this $4p4h$ 2^+ state (Fig. 2). Both the predicted energy and the relative cross sections agree well with the observed values. It might be useful to examine in-beam gamma-ray data from reactions such as $(\alpha, 2n)$ for

any evidence of a gamma-ray cascade involving these levels and higher-spin members of the $4p4h$ configuration. Additionally, because some mixing is suggested by the simple model, a further test would be to measure the expected monopole transitions between the mixed levels (see discussion in Ref. 13).

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Multifragmentation and Fission in the Reactions Nb + Au and Fe + Au at 50 to 100 MeV/A

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Experimental and theoretical studies of heavy-ion collisions at intermediate energies show that reactions leading to several complex fragments in the exit channel become important as one goes up in energy.¹⁻⁴ Systematic studies of correlations among the fragments are

essential for the elucidation of the mechanism of such multifragment processes. We report here some results from our recent studies of the reactions of Nb + Au at 50, 75, and 100 MeV/A and Fe + Au at 50 and 100 MeV/A, carried out at the Bevalac at the Lawrence Berkeley Laboratory.

Experiment and Results

To measure the correlations among the wide range of reaction products at intermediate energies, we have built a detector array with large geometric coverage and a wide dynamic range in energy and particle type. In Ref. 5, we give a detailed description of this system, called PAGODA.

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As described in last year's *Annual Report*,⁶ we observed three broad classes of fragments in these reactions: intermediate-mass fragments (IMF) with $4 < Z < 25$, fission-mass fragments (F) with $25 < Z < 50$, and heavy residues (HR) with $Z > 50$. Our preliminary analysis indicates that these are the products of three independent reaction mechanisms, corresponding to different impact-parameter ranges. These are (1) fission that occurs in very peripheral collisions, (2) heavy residues in less peripheral reactions, and (3) IMFs in "central" collisions. Results for both Nb + Au and Fe + Au systems in the 50- to 100-MeV/A energy range support these conclusions, as shown in the following discussion.

Relative yields for the various singles and coincidence event types are shown in Fig. 1 for Nb + Au and Fe + Au. These yields are normalized to the IMF yield in each case. In all cases, the yields are summed over the acceptance of the gas detectors. Preliminary estimates of the absolute cross sections indicate that, for both iron and niobium projectiles, the cross sections for IMF production are constant to within a factor of 2. Thus, we see no indication of rapid change in IMF production that is characteristic of lower energies. Relative to IMFs, the fission and HR rates decrease slowly with increasing energy. The detailed Monte Carlo calculations necessary to account for the acceptance of the detector modules are in progress.

Figure 2. Average charged-particle multiplicities, $\langle M \rangle$, for Nb + Au. Labels I, F, and R refer to IMF, fission-mass fragment, and heavy residue, respectively. Labels FF, IR, IF, and II denote binary coincidences. In each case, the three bars from left to right are for 50, 75, and 100 MeV/A, respectively.

Figure 1. Relative cross sections for various types of events, normalized to IMF cross section, for (a) Nb + Au and (b) Fe + Au. Labels I, F, and HR refer to IMF, fission-mass fragment, and heavy residue, respectively.

However, comparing coincident IMF rates to coincident fission rates already suggests a multiplicity of several for IMFs in all cases. This is in contrast to the results of Trockel and coworkers,⁷ who reported a hundredfold increase in cross section for IMFs with $Z > 3$ for lower-total-energy reactions with carbon,

oxygen, and argon projectiles in the energy range from 30 to 84 MeV/A.

The measurement of energetic, light, charged particles in coincidence with the various classes of fragments provides a relative measure of the impact parameter and energy deposition. Figure 2 shows the average charged-particle

multiplicity associated with different event types for Nb + Au. Results for Fe + Au are very similar. The multiplicities associated with binary fission events are lowest, showing that energy deposition is lowest and essentially independent of bombarding energy for these events. The multiplicities are highest for IMF events and other events that involve one or more IMFs, and these are similar in their multiplicity values. This is consistent with IMF formation in central collisions with large energy deposition. The variation of the multiplicities also suggests that the energy deposition increases with projectile energy. The multiplicities for events in which an IMF is detected in coincidence with a fragment in the fission-product mass range are much higher than those for binary-fission events. The fragments identified as fission fragments can thus be associated with two distinct reaction mechanisms. Binary fission is associated with small energy depositions. At high energy depositions, the single large remnant from a high-multiplicity event may have a mass in the binary-fission range. Warwick and coworkers⁸ made similar observations in their study of Ne + Au at 250 MeV/A. Heavy residues are associated with intermediate multiplicities. These residues appear to result from intermediate impact-parameter collisions, in which the system emits many particles in a short time scale, leaving a remnant too light to fission.

The correlations between the projectile fragments seen at forward angles and the target-like fragments detected at angles larger than 24 deg (Fig. 3) provide direct support for these conclusions on the centrality of the reactions. In Fig. 3, the abscissa is the Z of the largest fragment

Figure 3. The ratio between coincident and singles spectra of the Z of the largest projectile fragment detected at angles less than 12 deg, for different types of events.

($Z_{\max}$) detected in each event at angles less than 12 deg. The ordinate is the ratio of the coincidence and inclusive spectra. This ratio falls exponentially with Z for IMF events, indicating central collisions with very small projectile remnants. For the HR events, the peaking of the distribution at $Z_{\max} = 10$ to 20 indicates that these are events with intermediate impact parameters, in which a significant part of the projectile survives. The "fission" events show two peaks: a peak at high- Z values arising from peripheral collisions, in which a large projectile remnant is seen, and a peak at low Z arising from hard collisions in which, as already discussed, a fragment in the fission mass range is left behind. The $Z_{\max}$ distributions for events in which two fission fragments are detected (shown in the left panel in the bottom part of Fig. 3) and those in which an IMF is in coincidence with a fragment in the fission mass range (central panel) support this classification of the fission events into two groups.

Figure 4 shows examples of the Z distributions observed in Nb + Au reactions at the three bombarding energies. The top curve in each panel gives the inclusive Z distributions at 72 deg. The lower curve in each case is the distribution obtained when an IMF is detected in coincidence in at least one other PAGODA module. The coincidence Z distribution can be considered characteristic of the hard central collisions producing intermediate mass fragments. It extends smoothly well into the range that we call the "fission fragment region" ($25 < Z < 50$) in our analysis, thus supporting our

conclusion regarding the two separate mechanisms that produce fragments in this mass range. We note that the slope of the coincidence distribution for IMFs does not change significantly with beam energy. The slope of the mass distribution in fragmentation reactions has often been interpreted in the context of a liquid-gas phase transition in the expansion phase of the reaction. However, simulations using the quantum molecular dynamics (QMD) model⁹ indicate that the mass distributions generally have a

strong dependence on the impact parameter. At the same time, this model is able to reproduce quantitatively the meager experimental data available so far in this energy regime. We are applying the QMD model to simulate our reaction systems in collaboration with the Frankfurt group.⁹

Summary

We have made correlation measurements on the products from Nb + Au and Fe + Au reactions at 50, 75, and 100 MeV. At large

Figure 4. Distributions of Z observed at 72 deg from Nb + Au at (a) 50 MeV/A, (b) 75 MeV/A, and (c) 100 MeV/A. Upper curves: inclusive distributions; lower curves: distributions in coincidence with at least one other IMF in the detector system.

impact parameters, fission of the target is observed in collisions with small momentum transfer. At medium impact parameters, the target-like system loses energy and mass through particle emission and, because of its reduced fissionability, survives as a heavy residue. In the most central collisions, the system becomes increasingly unstable, resulting in a significant number of intermediate-mass fragments and large multiplicities for light particles, sometimes leaving a residual fragment in the fission-fragment mass range. The reaction

mechanisms are similar for both target-projectile systems over the energy range studied. The cross sections for the major classes of products change very little over the energy range studied here. We are well above the threshold for forming intermediate mass fragments. Analysis of the data to extract detailed correlations is in progress.

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Thermodynamics of the Aqueous Coordination of Thorium with the Iodate Anion

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We have recently measured enthalpy values for three thorium complexes with fluoride¹ as well as for thorium complexes with a variety of amine-N-polycarboxylic acids.² We are interested in the study of thorium coordination thermodynamics because Th(IV) is a useful model for Pu(IV) chemistry^{3,4} without the attendant radiation hazards.

The ligand under investigation in the present work is iodate. Iodic acid belongs to an important group of intermediate-strength electrolytes,⁵ and we report here the results of a study of the aqueous complexation of the thorium cation with iodate species.

Experimental

We synthesized a 0.02M Th⁴⁺ working solution from 99.99% pure starting material, acidified it to pH 1.2 with HClO₄, and adjusted the ionic strength (μ) to 0.5M with NaClO₄. The titrant employed was 0.1M NaIO₃ at pH 7.0 and $\mu = 0.5M$ (NaClO₄). Details of solution synthesis and characterization have been given elsewhere,⁶ and all materials were of analytical reagent-grade quality or better.

We have previously described the quasi-adiabatic titration calorimeter used for this work.⁷ Initial volume of the Th⁴⁺ calorimeter solution was 50.0 ml, while we typically added titrant in 0.20- to 0.50-ml aliquots.

These experiments sampled the complete range of metal-ligand speciation up to the point of Th(IO₃)₄ precipitation, and precipitation occurred at an average ligand number $\bar{n} \approx 0.25$ in this system.

We also performed experiments to measure the enthalpy of formation of HIO₃; the NaIO₃ solution was titrated into $\mu = 0.5M$, pH = 1.4 HClO₄ to determine ΔH_{011} . (The indices "011" refer to the number of atoms of metal, hydrogen, and ligand, respectively, in the complex; thus, "101" indicates the reaction $M + L \leftrightarrow ML$, "011" indicates $H + L \leftrightarrow HL$, etc.) We accomplished heat-of-dilution or blank runs by titrating 0.5M NaClO₄ solution with iodate.

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We conducted all calorimetry experiments at $25.00 \pm 0.01^\circ\text{C}$, with temperature stability of the thermostat maintained to $\pm 0.0003^\circ\text{C}$.

Results and Discussion

Low solution pH was required to prevent metal hydrolysis reactions, and HIO_3 formation could thus compete with thorium-ligand reactions during calorimeter experiments. We have described in detail elsewhere the apportionment of measured heats into dilution, acid, and metal contributions, as well as the requisite computation of detailed solution speciation by nonlinear regression.¹ We used stability constants for three thorium-iodate complexes at $\mu = 0.5\text{M}$ (NaClO_4) and $T = 25^\circ\text{C}$ from Day and Stoughton.⁸ Similarly, the HIO_3 acid constant came from Bonner and Prichard⁹ and is the average of two ion-exchange determinations at $\mu = 0.45\text{M}$. We summarize all stability-constant data used for the speciation calculations in Table 1.

We corrected the empirical heats for the formation of HIO_3 from the computed change in moles of acid

(Δn_{011}) and the value $\Delta H_{011} = 7.1 \pm 1.2\text{ kJ/mol}$. We obtained the latter datum in separate calorimeter runs in our laboratory, and it is the result of 20 independent measurements. Previous literature values for ΔH_{011} are $2.8 \pm 0.5\text{ kJ/mol}$ at $\mu = 0$ (see Refs. 5 and 10) and $4.6 \pm 0.02\text{ kJ/mol}$ in an ideal 1M standard state.¹¹

Under the experimental conditions reported here, empirical heats generated by the thorium-iodate system were small and fell in the calorimeter's nonlinear-response region below 200 mJ (Ref. 7). Thus, as previously described,^{1,7} we normalized the thorium-iodate data to the protonation enthalpy of the tris-(hydroxymethyl) aminomethane (TRIS) primary calibration standard. We then calculated reaction enthalpies from the calorimeter and speciation data by means of multivariate, nonlinear, least-squares analysis.¹

We summarize the thermodynamics of the thorium-iodate system at $\mu = 0.5\text{M}$ in Table 2. The enthalpy data are the results of 33 independent determinations and are from five separate calorimeter runs that spanned a range of a factor of 6 in

measured heat. The errors we report are 1σ standard deviations and reflect only the uncertainties in the calorimeter temperature measurements. We have given specific detail on analysis techniques and error propagation elsewhere.^{6,7} Because we have not included uncertainties in the speciation-computation input parameters, our reported errors are minimum values associated with these experiments.

We were able to reliably extract only the first two reaction enthalpies from our data, probably the result of the onset of $\text{Th}(\text{IO}_3)_4$ precipitation occurring at such small $\bar{n}$. Although we place reasonable confidence in the value for ΔH_{101} (6% reported uncertainty), a similar statement cannot be made for ΔH_{102} (>100% error). The only prior literature reference to $\text{Th}(\text{IO}_3)_x$ enthalpy measurements, of which we are aware, is an unpublished value (F. I. Khalili, E. N. Rizkalla, and G. R. Choppin, Florida State University, Tallahassee) for ΔH_{101} at 25°C and $\mu = 1\text{M}$ cited in Ref. 12. That value of $6.5 \pm 0.4\text{ kJ/mol}$ is a factor of 2 more endothermic than the result reported here.

Table 1. Stability constants used to calculate general solution speciation at $\mu = 0.5\text{M}$ and $T = 25^\circ\text{C}$.

Constant	Value	Ref.
$\text{HIO}_3 \log \beta_{011}$	0.46 ± 0.02	9
$\text{Th}(\text{IO}_3)^{3+} \log \beta_{101}$	2.88 ± 0.05	8
$\text{Th}(\text{IO}_3)^{2+} \log \beta_{102}$	4.79 ± 0.07	8
$\text{Th}(\text{IO}_3)_3 \log \beta_{103}$	7.15 ± 0.10	8
pK_w	13.74 ± 0.02	10

Table 2. Thermodynamic parameters for the $\text{Th}(\text{IO}_3)_x$ system at $T = 25^\circ\text{C}$ and $\mu = 0.5\text{M}$ (NaClO_4).

Complex	<i>i</i>	$-\Delta G_{10i}^a$ (kJ/mol)	ΔH_{10i} (kJ/mol)	ΔS_{10i} (J/mol · K)
$\text{Th}(\text{IO}_3)^{3+}$	1	16.4 ± 0.3	3.3 ± 0.2	66 ± 1
$\text{Th}(\text{IO}_3)_2^{2+}$	2	27.3 ± 0.4	4 ± 5	100 ± 20
$\text{Th}(\text{IO}_3)_3$	3	40.8 ± 0.6	—	—
^a Ref. 8.				

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Tritium Oxidation Kinetics

R. A. Failor, P. C. Souers, F. Magnotta, and S. G. Prussin*

The biological toxicity of tritium in the form of water (HTO or T_2O) is 25,000 times that of molecular tritium (HT or T_2). Therefore, operators of a tritium-handling facility must know what percentage of tritium in the work environment is present as tritiated water and the rate of conversion from the molecular form to the water form.

To better understand the formation of tritiated water, we studied the mechanism of one of the most basic reactions, tritium oxidation. As we discussed in earlier *Annual Reports*,¹⁻³ we modeled the oxidation mechanism and tested the model predictions by experimentally monitoring the time variation of one of the primary intermediate species, ozone.

Model Predictions

In the major phase of the tritium-oxidation reaction, two chains of reactions control the production of T_2O :

Both chains result in the same overall reaction, combining ozone and hydroperoxyl to form T_2O . The model predicted that sufficient ozone would be produced for in situ monitoring.

The reactions controlling the ozone concentration can be simplified into two equations:

$$\frac{d[O_3]}{dt} \Big|_{\text{initial}} = k_a [O]_{ss}, \quad (6)$$

$$[O_3]_{ss} \equiv \frac{k_a [O]_{ss}}{k_b [TO_2]_{ss}}, \quad (7)$$

which tie the initial rate of ozone production to the steady-state concentration of oxygen atoms, $[O]_{ss}$, and the steady-state ozone concentration, $[O_3]_{ss}$, to the steady-state hydroperoxyl concentration, $[TO_2]_{ss}$. The model can link each of these terms to the initial tritium concentration, $[T_2]_0$, giving:

$$\frac{d[O_3]}{dt} \Big|_{\text{initial}} = k_c [T_2]_0, \quad (8)$$

$$[O_3]_{ss} \equiv k_d [T_2]_0^{0.3}. \quad (9)$$

Comparison of Experimental Results and Model Predictions

We used ultraviolet-absorption spectroscopy to determine the time variation of the ozone concentration for mixtures of 0.01 to 1.0 mol% T_2 in O_2 (1 atm, 298 K). In a number of experiments, we added H_2 to T_2 - O_2 mixtures to provide insight into the differences between the chemical and radiologic effects of the tritium in the reaction. We also investigated

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the effects of the reaction vessel's walls on the measured ozone concentration by varying the surface-to-volume ratio of the vessel.

In more than 21 experiments, the measured ozone concentration initially climbed steadily, then slowed and leveled off to a steady value ($[O_3]_{ss}$). Figure 1 shows both the model predictions and the experimental results for T_2 - O_2 mixtures at five initial T_2 concentrations. Clearly, the pattern of the ozone concentration time variation predicted by the model is the same as that measured in the experiments. This can be expressed quantitatively in the form:

$$[O_3] = [O_3]_{ss} \{1 - \exp(-t/\tau)\}, \quad (10)$$

where t is the time and τ is a system-dependent variable. Qualitatively, the experimental results were in agreement with the model predictions, but there were quantitative discrepancies.

The initial rise in the ozone concentration was predicted to be caused by the production of ozone from oxygen atoms formed as a result of the tritium beta radiolysis of the oxygen and was predicted to vary linearly with the initial T_2 concentration. As shown in Fig. 2, the experimental initial rate was, indeed, linear in $[T_2]_0$, but with an experimental value one-third of that predicted. In T_2 - O_2 mixtures, the steady-state ozone concentration was predicted to be dependent on $[T_2]_0^{0.3}$, but as shown in Fig. 3, the measured values varied approximately as $[T_2]_0^{0.6}$, which resulted in a value of $[O_3]_{ss}$ four times that predicted for a 1.0% T_2 - O_2 mixture. These quantitative differences are quite noticeable in the comparison of the experiment and the model shown in Fig. 1.

To help us understand the influences of the radiolytic and chemical properties of tritium in this system, we added H_2 to a number of experiments to provide the chemical properties of tritium without the radiolytic effects. As discussed in last year's *Annual Report*,³ the model predicted a relatively small reduction in $[O_3]_{ss}$ as a result of the addition of H_2 . In the experiments, we measured a much larger reduction in $[O_3]_{ss}$. This indicates that the model underestimates the effect of hydroperoxy, both tritiated $[TO_2]$ and protiated $[HO_2]$, because Eq. (7) shows that $[O_3]_{ss}$ should be inversely proportional to the hydroperoxy concentration.

We examined the model to determine what features accounted for these discrepancies. Using a general sensitivity analysis, we determined that two-thirds of the factor-of-3 discrepancy in the initial rate of ozone production could be accounted for by uncertainties in the input values for the rate constants of the ion-electron recombination rates. However, the overall uncertainty in the rate constants could not account for all of the differences between the experimental and calculated values of $[O_3]_{ss}$.

We performed an extensive sensitivity analysis on the model, concentrating our efforts on those reactions of importance to the ozone cycle. We varied more than 20 parameters,

Figure 1. (a) Model predictions and (b) experimental results for five T_2 - O_2 mixtures.

with a range of values for each parameter. In addition to checking the values of the existing model-input parameters, we checked some of the basic assumptions of the

model, such as the importance of oxygen-ion clusters, the formation of O_2 and its subsequent reactions, and the possibility of reactions of impurities in the gases.

Figure 2. The model-predicted and experimentally measured initial rates of ozone production, both of which vary linearly with $[T_2]_0$. The measured values are one-third the predicted values.

Figure 3. For T_2 - O_2 mixtures, the predicted dependence of the steady-state ozone concentration on $[T_2]_0$ is less than the experimentally measured dependence. As a result, the measured value for 1.0% T_2 is four times the predicted value.

We found that the changes that would reduce the model's predicted initial rate of ozone production would also reduce $[O_3]_{ss}$, as in Eqs. (6) and (7), which was contrary to the findings of the experiment. If changes were made to increase the depletion effect of hydroperoxyl on ozone, as was indicated by the H_2 addition experiments, this also decreased $[O_3]_{ss}$ in the non- H_2 cases. No changes tested could account for the change of the predicted $[O_3]_{ss}$ dependence from $[T_2]_0^{0.3}$ to the measured $[T_2]_0^{0.6}$. Further experimentation and modeling are needed to understand these discrepancies.

To determine the importance of the reactions with the vessel wall on the measured ozone concentrations, we ran several T_2 - O_2 experiments in a secondary cell with a surface-to-volume ratio 2.7 times that of the primary reaction cell. We found that, at 1% $[T_2]_0$, the change in surface-to-volume ratio had no measurable effect on the ozone concentration. However, for 0.1 and 0.03% $[T_2]_0$, we measured a decrease in $[O_3]_{ss}$ that was larger for the lower value of $[T_2]_0$. This is indicative of a limited surface adsorption of ozone at a level that would be within the uncertainty for 1.0% T_2 but would be measurable for less than 0.1% T_2 . Further experimentation will be required to determine the level of ozone adsorption that can account for these results. However, the surface effects do not appear to be sufficient to account for the total discrepancies between the model and experiment.

Summary

This is the first time that an intermediate reaction in the tritium-oxidation reaction has been monitored and the first time that the system has been studied in situ. We find that the first extensive mechanistic model of tritium oxidation predicted the behavior of one of the primary intermediates qualitatively, but the model requires refinement for successful quantitative agreement.

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Isotopic Tracers of Lead Contamination in the Great Lakes

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The predominant source of lead contamination in the Great Lakes is the atmospheric deposition of industrial lead. The primary contribution is still gasoline combustion, even though this input has decreased by an order of magnitude in the last decade. The question of whether lead contamination in surface waters of the Great Lakes has also decreased during this same period cannot be clearly answered because previous measurements are now suspect. The data suggest that most previous work may have had procedural blank levels that were greater than the actual lead contents of the surface waters.¹ In this study, we adapted to Lakes Ontario and Erie the ultraclean techniques developed for lead isotopic studies of seawater.

In addition to the total lead content of the water, another important issue is the atmospheric dispersion of contaminant leads in the Great Lakes. Of the potential inputs of lead to the atmosphere, we want to

determine which are responsible, and to what degree, for the lead in any given area of the Lakes. These determinations will be important because they increase our understanding of the atmospheric transport of lead and provide isotopic fingerprints for tracing other anthropogenic contaminants that have similar sources and geochemical transport properties.

Our approach in this work was to determine both the amount and isotopic composition of lead in surface waters in order to address the above issues. In particular, we used the fact that industrial leads from the U.S. and Canada have different isotopic compositions; thus, the isotopic data provide a means of discriminating between these two major sources of industrial contamination. This work constitutes the first accurate determination of lead isotopic compositions in any freshwater system.

Experimental Results

Two-liter samples of water from a depth of approximately 1 m in Lakes Ontario and Erie were collected from a raft in August 1987 at numerous Canadian environmental monitoring stations, as indicated in Fig. 1. Elemental concentration and isotopic composition were measured in filtered (<0.4- μ m) samples by thermal ionization mass spectrometry. The sum of lead contamination (sampling, storage, and analytical) for these measurements was <2%; the isotopic composition of the lead blank was indistinguishable from common U.S. industrial leads (e.g., $^{206}\text{Pb}/^{207}\text{Pb} = 1.22$). Mass fractionation corrections for the lead isotopic composition were derived from concurrent analyses of National Institute of Standards and Technology Standard Reference Material (SRM) 981. Typical 2σ uncertainties are $\pm 0.1\%$ for $^{206}\text{Pb}/^{204}\text{Pb}$ ratios and $\pm 0.04\%$ for $^{206}\text{Pb}/^{207}\text{Pb}$ ratios.

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Figure 1a shows the projected contours of the $^{206}\text{Pb}/^{207}\text{Pb}$ ratios, based on the measured ratios at each sampling site. Spatial gradients in the lead isotopes are clearly evident for both lakes. Most of the $^{206}\text{Pb}/^{207}\text{Pb}$ ratios (1.147 to 1.160) in the western and central basins of Lake Ontario were within the normal range of urban aerosols in the Toronto metropolitan area (1.151 ± 0.010). In the eastern basin, this ratio rose to values that were intermediate

to urban aerosols from Canada and the U.S. (1.221 ± 0.009). This pattern is consistent with variations in the $^{206}\text{Pb}/^{207}\text{Pb}$ ratios of lead-containing aerosols collected along the northern shore of Lake Ontario by Sturges and Barrie.² They found that, when the winds were from the north, the ratio ranged from 1.10 to 1.16, which was interpreted as being characteristic of Canadian industrial leads; but when the winds were from the south, the ratios were about 1.19, which is

intermediate between the U.S. and Canadian industrial leads. The distributions of lead isotopic composition in the surface waters of Lake Ontario that we have determined, therefore, are consistent with the atmospheric dispersion of industrial lead aerosols from the U.S. and Canada.

Stable lead isotopic composition of surface waters in Lake Erie exhibited similar spatial gradients, as shown in Fig. 1a. The $^{206}\text{Pb}/^{207}\text{Pb}$ ratio (1.157) of surface waters in the northern region of the lake was similar to those of waters in western Lake Ontario and urban aerosols in eastern Canada. In the central and southern regions of Lake Erie, the ratios were closer to those of urban aerosols in midwestern cities within the U.S. Again, this distribution is consistent with the Sturges and Barrie² measurements along the shore of Lake Erie.

The predominance of anthropogenic lead inputs to the lakes was further illustrated by the distribution of dissolved ($<0.4\text{-}\mu\text{m}$ filtered samples) lead concentrations, shown in Fig. 1b. Lead content was elevated near major urban areas where inputs of industrial lead [measured in metric tons per year (t/y)] from atmospheric emissions (379 t/y), industrial effluents (17 t/y), municipal effluents (142 t/y), and other anthropogenic sources (54 t/y) are concentrated. Of special note is the unusually high concentration found in Hamilton Harbor (291 pmol/kg), where substantial municipal and industrial effluents with relatively high lead content are input. In general, the western part of Lake Ontario and the southwestern part of Lake Erie show elevated lead content, compared with the central and eastern areas of these lakes, where the lead abundance is typically less than 30 pmol/kg.

Figure 1. Projected distribution of lead isotopic composition and concentration in surface waters of Lakes Ontario and Erie in August 1987. Sampling locations are shown by the filled circles. (a) The projected distribution of $^{206}\text{Pb}/^{207}\text{Pb}$ ratios. (b) The distributions of dissolved lead (in pmol/kg).

The spatial gradients in both lead isotopic composition and lead concentration in surface waters of the Great Lakes attest to the rapid removal of lead from these waters. The steady-state summer residence time of dissolved lead is estimated to be 5 and 7 d, respectively, for Lakes Ontario and Erie. Although these estimates are based on overly simplistic assumptions, they are at least one order of magnitude below previous estimates, which were based on samples that were probably dominated by high lead background levels. The short residence times provide evidence that the dissolved lead is rapidly scavenged by the formation of nuclide/particle surface-site complexes, including dissolved organic carbon peptization and particulate organic carbon (POC) coagulation. These processes control the distribution of lead in aquatic systems and are particularly important in waters with high organic loadings. Lead, therefore, should be rapidly scavenged in the Great Lakes during summer algal blooms, when POC production is relatively intense.

The observation of $^{206}\text{Pb}/^{207}\text{Pb}$ gradients clearly calls for at least two distinct sources of lead. We can use the complete set of isotopic ratios to examine how many isotopic components are required to account for the lead in surface waters and then speculate on the origin of these sources. Best-fit correlation lines were calculated for the various three-isotope, two-dimensional plots that can be made with the four stable isotopes of lead. An example of these plots is shown in Fig. 2. If the data represent mixing of only two isotopically distinct components, a straight line should provide a statistically good fit (reduced $\chi^2 \approx 1$). The

various plots give reduced χ^2 values of 1.6 to 2.7. This degree of scatter suggests that at least three isotopic components are present in these samples, but we emphasize that the data predominantly reflect mixing of only two components. The good fit to a line in Fig. 2 reinforces this conclusion. The fact that two isotopic components can account for nearly all of the isotopic variations among these water samples is consistent with our interpretation that industrial lead inputs from the U.S. and Canada represent the two components and that, in each case, the various emissions have been extensively and rapidly mixed in the atmosphere. However, we point out here that the low $^{206}\text{Pb}/^{207}\text{Pb}$ end member is not consistent with the previous measurements of urban aerosols in eastern Canada.² This conclusion rests primarily on the two extreme points in Fig. 2; however, because the best-fit line does not change significantly when these two points are excluded, we infer that all of our samples have a component with a $^{206}\text{Pb}/^{207}\text{Pb}$ ratio lower than 1.056. The Sturges and Barrie² analyses of atmospheric particulates in Toronto included one sample with an anomalously low $^{206}\text{Pb}/^{207}\text{Pb}$ ratio (1.10), but they tentatively attributed this result to an additional component from a secondary lead smelter located 10 km away. Their data do not include the minor ^{204}Pb isotope, so we cannot compare it with our data base. Our tentative interpretation for the suite of samples we collected is that the anomalously low $^{206}\text{Pb}/^{207}\text{Pb}$ samples are part of the main two-component mixing trend, as opposed to reflecting an infrequent contribution from an additional third component. Confirmation of

this suggestion will require analysis of all lead isotopes for aerosols, as well as measurements of the postulated sources of the various isotopic components.

Summary

We have demonstrated that analyses of lead isotopic composition and concentration in the surface waters of the Great Lakes provide a means of fingerprinting the sources of lead contamination to these lakes. The isotopic composition demonstrates that essentially all of the lead deposited in the surface waters of Lakes Ontario and Erie is currently derived from Canadian and U.S. industries or sources, primarily via aerosol transport. Spatial gradients in the isotopic composition and corresponding lead concentration attest to the rapid scavenging of lead in

Figure 2. Lead isotopic composition from Lakes Ontario and Erie. The best-fit line to all of the data is shown; the 2σ uncertainties are comparable to the size of the symbols, except for the two points with error bars. The good correlation demonstrates that the lead predominantly reflects mixing of two isotopic components for these two lakes. The $^{207}\text{Pb}/^{206}\text{Pb}$ ratios for atmospheric particulates are 0.819 ($^{206}\text{Pb}/^{207}\text{Pb} = 1.221$) for the U.S. and 0.867 ($^{206}\text{Pb}/^{207}\text{Pb} = 1.151$) for Canada.² See text for discussion of the sources of the two isotopic end members.

the lakes and conform to the expected atmospheric dispersion of industrial lead aerosols.

Additional measurements can be used to monitor future declines in atmospheric emission of lead from gasoline combustion in Canada and the U.S. This source still accounts for 15,400 t/y of lead into the atmosphere, whereas other sources of atmospheric emissions are less, e.g., municipal waste incineration (2800 t/y), industrial processes (2300 t/y), coal combustion (778 t/y),

and inputs from wastewater effluents and solid-waste disposal. These minor sources may, in the future, be individually identified and traced by their lead-isotopic composition. A more immediate goal of future work will be to identify the extent to which the dispersion of lead aerosols can also serve as a tracer for associated contaminants. An important case is that of acid rain. Because atmospheric residence times of lead and acid-rain precursors are comparable, we may be able

to identify uniquely the relative contributions of the various sources of acid rain in a given area, once the lead isotopic composition is well established for each of the sources.

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Trace-Element Analyses of Geologic Samples by ICP-MS: Case Studies and Examples

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The relatively new technique of inductively coupled plasma-mass spectrometry (ICP-MS) enables simultaneous and rapid determination of more than 60 elements to the parts-per-trillion (ppt or 10^{-12} g/g in solution) level in geologic samples.¹ Trace-element analyses of rock samples have been done by methods such as neutron activation analysis (NAA) and x-ray fluorescence analysis (XRFA). However, these methods are capable of analyzing only smaller subsets of trace elements with higher detection limits.

In the following studies, we prepared rock samples for ICP-MS analysis by two methods. One method was to digest powdered rock samples by acid ($\text{HF} + \text{HNO}_3$) in closed Teflon beakers in a microwave oven. The second method was to fuse mixtures of rock powder and ultrapure

LiBO_2 flux (ratio 1:5) in a furnace at 1050°C with immediate dissolution of the molten product in 1.5M HNO_3 . Accurate analysis of trace-element abundances in any material requires complete dissolution. Natural rock samples vary in texture and usually consist of mixtures of minerals that vary in their resistance to attack by acids. Incomplete dissolution of resistant mineral phases, though finely powdered, will bias analytical results. To judge the accuracy and success of sample preparation, standard reference rock samples were prepared by both methods and analyzed. Flux-fusion produces an easily dissolved glass that yields accurate analyses, though volatile elements such as lead and arsenic are lost from the sample. After some developmental work, the microwave method was successful and has

some advantages, including retention of volatile trace elements and better detection limits.

Total dissolved solids in final analyte solutions (in 0.2M HNO_3) should be about 1 mg/ml, to prevent accumulating material on the torch of the ICP-MS and possible cross-contamination between samples. The effective dilutions of rock material in analyte solutions prepared by microwave digestion and flux fusion were 1:1000 and 1:5000, respectively. Given detection limits of a few ppt in solution, corresponding detection limits of most trace elements in rocks prepared by the two methods were approximately 2 and 10 ppb (10^{-9} g/g). Determination of abundances of 35 trace elements ranging from mass 45 to 238 (scandium to uranium) in standard reference rock materials and sample rocks was

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achieved by analysis of multi-element standard solutions prepared from commercially available elemental standards that were diluted to ranges expected in the analyte solutions. Analyses of standard solutions, standard rocks, and study samples were performed by conventional nebulization into the argon plasma.¹ All analyses discussed here were performed on a second ICP-MS instrument installed in a clean, controlled-environment laboratory in the limited-access controlled area. This location has greatly facilitated productive collaborations with university-based researchers lacking additional security clearances.

Among the many trace elements detectable in various rock samples, the rare-earth elements (REE), lanthanum to lutetium, are very useful in identifying and evaluating geologic processes. In the following studies, the REE and other trace elements were used to identify the original submarine affinity of a suite of volcanic rocks, lateral variations in seawater composition, former specific depositional environments of sedimentary rocks, and the origin and depositional environment of ancient sedimentary iron ores, all now exposed on land.

Troodos Complex, Cyprus

The mid-oceanic ridges today are centers of intense submarine volcanic activity. These submarine ridges are sites of new crustal formation that result from extensional stresses within the oceanic crust. The ridges consist of continuous linear chains of volcanic vents and fissures that exude lava created by the melting of the Earth's upper mantle above rising limbs of large convection cells in the mantle. These oceanic ridges are offset at various intervals along their

lengths by major faults called transform faults. The chemistry of the erupted lavas, termed mid-ocean ridge basalts (MORB), yields clues to the processes that have modified the composition of the upper mantle and their own composition during their ascent, cooling, crystallization, and aggregation to form the oceanic crust. The Atlantic Ocean is an example of a mature ocean with a mid-ocean spreading ridge that resulted from the separation of Europe and Africa from North and South America beginning about 140 million years (Ma) ago. In contrast, the Red Sea is a younger ocean basin-and-ridge system that began to separate Africa and Arabia approximately 10 Ma ago.

The Troodos complex in Cyprus preserves the fossilized intersection of a spreading ridge with a transform fault zone. Geochemical studies of samples dredged from modern

ridges suggest that magmatism is episodic and that modern ocean ridges are chemically zoned, especially near transform fault zones. The exposure of old oceanic crust, as in the Troodos complex, allows three-dimensional sampling of an ocean ridge. Samples were analyzed from two suites: one collected along the axis of the fossil spreading center, 16 km to the transform fault zone (the Arakapas Fault Zone), and one from a fossilized volcanic-seamount complex that formed from multiple magmatic events.

Modest increases in REE abundances and cerium/ytterbium ratios in samples collected from the seamount are consistent with chemical fractionation of the later lavas from the earlier lavas (Fig. 1). The gabbro sample represents a crystal cumulate, and the late-stage volcanics represent residual magmas;

Figure 1. REE abundances in selected representative samples from the seamount complex, Troodos complex, Cyprus, normalized to average chondritic abundances and plotted in order of increasing atomic number.

both formed during crystallization of magma in a magma chamber. All samples are depleted in light REE, relative to heavy REE, when normalized to average chondritic abundances (Fig. 1). Samples collected perpendicular to the transform fault zone show a distinct chemical zonation; total REE abundances and cerium/ytterbium ratios increase away from the transform fault (Fig. 2). This significant variation in total REE abundances and cerium/ytterbium ratios is a result of complex and variable partial melting processes associated with magma formation within the upper mantle, rather than subsequent chemical fractionation of magmas during crystallization in a magma chamber at

more shallow depths. Our results contradict models for magma evolution along ocean ridges that are based on analyses of limited numbers of samples dredged along ocean ridges; these earlier results suggested that magmas adjacent to fracture zones evolve by crystal fractionation rather than by partial melting processes.²

Sedimentary Environments

We observe differences in both total abundances of REE and relative fractionations among REE in sedimentary rock samples, and these differences reflect distinct depositional environments within a former ocean basin. On the basis of relative cerium depletions and total REE in a sequence of sedimentary rocks from Marin County, California, which were deposited from 180 to 100 Ma ago, geochemical signatures of three specific depositional environments can be recognized: spreading-ridge proximal, ocean-basin floor or abyssal plain, and the continental margin. This continuous sequence consists of alternating chert (very rich in silicon) and shale (containing clay particles) sedimentary rocks, bounded at the base by a submarine basalt flow and metal-rich sediments thought to have been formed very near the crest of a former spreading ridge. This well-studied sequence, based on geologic criteria, represents deposition of suspended and dissolved material from seawater above a point location that progressively moved away from an actively spreading mid-ocean ridge, as described earlier, toward a continental margin.

Adsorption from seawater is the most important mechanism of incorporation of REE in deep-ocean sediment. Two important controls on the abundance of REE in marine sediments are the amount dissolved

in seawater and the rate of accumulation of sediment. The latter determines the exposure time of a planar layer of sediment to a virtually infinite reservoir of seawater. These two controlling factors vary dramatically across an ocean basin from the volcanically active mid-ocean spreading ridge to the continental margin. An additional factor present only near the spreading ridge is the precipitation of iron and manganese oxyhydroxides, which rapidly scavenge REE and other elements from seawater.^{3,4} Thus, seawater near the spreading ridge will contain relatively lower abundances of dissolved REE. Relatively insoluble Ce(IV) is scavenged preferentially by the iron and manganese particulate oxyhydroxides, resulting in ridge-proximal seawater with a greater relative cerium depletion than that observed in open-ocean water. The prediction that siliceous sediments accumulating near the spreading ridge should have the lowest total abundances of REE and the greatest relative cerium deficiencies is supported by our results for the Marin County marine sediments.⁵ As shown in Fig. 3, the magnitude of the cerium deficiency decreases upward in the sequence (to younger layers) in both cherts and shales. Total REE abundances increase upsection, especially in the cherts, as predicted in our model.⁵

Iron Formations

The depositional environment of even more ancient sedimentary rocks, specifically metal-rich, banded-iron formations (BIFs) more than 2 billion years (Ga) old, remains controversial.⁶⁻¹⁰ These sequences of economically valuable sedimentary rocks have unique characteristics and occur in ancient continental cores in all of the major continents. Iron formations typically consist of

Figure 2. Lava samples collected along a transect in the Troodos complex, Cyprus, show a distinct chemical zonation. (a) Abundances of lanthanum and cerium and (b) cerium/ytterbium ratios plotted with respect to the location of the fossil transform fault (Arakapas Fault Zone).

alternating silica-rich cherts, iron-rich cherts, and minor interbedded shales and have a banded appearance in outcrop—hence, the name. Many occurrences, especially those from Western Australia, display microbanding with extensive lateral continuity and consist of iron-rich and silica-rich layers averaging 0.1 to 0.2 mm in thickness. Since BIFs may originate by chemical precipitation of iron oxides and colloidal silica from large bodies of water, the microbanding is thought to represent annual variations in redox conditions. Larger-scale cyclic variations within BIF sequences may reflect ancient solar cycles and rhythmic changes in local tectonic conditions and water chemistry. Detailed geochemical studies of BIFs will yield valuable information on the composition and conditions of the Earth's early hydrosphere and atmosphere.

We are obtaining trace-element abundances in samples of BIFs and associated shales that have been analyzed for their neodymium isotopic compositions.¹¹ Data for samples from a continuous 700-m drill core of the Brockman Iron Formation from the Hamersley Basin, Western Australia, define an isochron with an age of 2310 ± 60 Ma, in agreement with geologic age estimates. This colinearity for BIF samples varying widely in lithology and parent/daughter samarium/neodymium ratios strongly suggests that (1) the dissolved and suspended (eroded) BIF components within the Hamersley Basin were derived from the same source, and (2) samarium/neodymium ratios were fractionated during erosion of the surrounding crust and uptake of weathering products into solution. For a depositional age of 2310 Ma, the Brockman samples—including silica-rich cherts, iron-rich cherts, and shales—have initial neodymium

isotopic compositions indicative of a crustal source of the neodymium rather than the hydrothermal input from a mid-ocean ridge suggested by reconnaissance studies.⁷ Thus, the main source of the chemically precipitated cherts was the same as that of the shales, namely, the sub-aerial erosion of surrounding

granitic crustal rocks. Likely crustal source rocks that bounded the Hamersley Basin are presently exposed in Western Australia and have been dated at up to 3.7 Ga.

Abundances of REE in Brockman BIF samples normalized to average shale values confirm suggestions⁸ that short-term fluctuations in redox

Figure 3. Shale-normalized REE abundance patterns in interbedded chert and shale in an exposed stratigraphic section from Marin County, California, plotted in stratigraphic order. Numbers on the right side of each plot are the stratigraphic position (in meters) above a basal basalt, and numbers to the left are the inferred distance (in kilometers) from a former mid-ocean spreading ridge, assuming a sedimentation rate of 82 m/100 Ma. The dashed lines indicate a section covered and obscured by soil; no samples were obtained.

conditions produced the micro-banded texture made up of iron-rich and iron-poor submillimeter layers. Shales and silica-rich cherts, though vastly different in total REE content, do not display relative REE fractionations, whereas iron-rich cherts display small relative enrichments in europium (Fig. 4). Under sufficiently reducing conditions, Eu(III) may be preferentially reduced to Eu(II) even though other REE remain trivalent. This permits enhanced adsorption of Eu(II) into sites normally occupied by divalent cations such as calcium and strontium, resulting in a relative enrichment of europium. Reducing conditions responsible for Eu(II) also reduced iron, which precipitated as iron hydroxides, and alternated with oxidizing conditions under which shales and silica-rich cherts were

deposited. Relative cerium deficiencies, seen in modern seawater and sediments up to 180 Ma old (Fig. 2), are absent in BIFs (Fig. 4) and also suggest more reducing conditions prevalent in oceans 2 Ga ago.

Future Work

This research was carried out in only a few months and demonstrates the utility of simultaneous, multi-element, trace-element-analysis studies. The ICP-MS instrument has revolutionized the rapid acquisition of such data. We plan to improve precision by use of enriched isotope spikes for isotope-dilution analysis of selected trace elements by ICP-MS and dissolution of samples in microwave digestion vessels. We are developing an alternative method of sample introduction by computer-controlled electrothermal

vaporization, which should increase sensitivity by more than a factor of 100, relative to solution nebulization, for many elements. Future projects include:

- Analysis of pore waters extracted from deep-sea sediments to ascertain low-temperature alteration and element mobility.
- Analysis of metals in marine organisms near a wrecked ore carrier.
- Analysis of trace elements in waters and precipitates from a geothermal test well near Kilauea Volcano in Hawaii.
- Ongoing analysis of osmium-isotopic composition of meteorites and terrestrial rock samples.

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Figure 4. Shale-normalized REE abundance patterns in selected representative samples from the Brockman Iron Formation, Hamersley Basin, Western Australia.

4

Containment

Since the U.S. and the Soviet Union signed the Partial Nuclear Test Ban Treaty in 1963, all U.S. nuclear tests have been conducted underground. This treaty not only precludes atmospheric testing of nuclear explosives but also prohibits the crossing of international borders by detectable quantities of radioactive material from nuclear tests. In addition, it is federal policy that quantities of radioactive material above strictly defined guidelines should not exit the boundaries of the Nevada Test Site (NTS) and should not be inadvertently released on the NTS. The Laboratory's Containment Program is responsible for preventing the release of radioactivity and radioactive debris from LLNL's underground nuclear tests. To this end, we play many roles in conducting a nuclear test, from planning an event to analyzing data gathered during and after detonation.

When a nuclear test is first placed on the test schedule, it is sited, in conjunction with representatives of LLNL's Field Operations Program, in the most appropriate existing drill hole (a stockpile of holes has already been drilled at the NTS). The depth of a hole that has already been drilled determines, in large part, the yield of the event that can be expended in that hole. If no suitable hole exists, a new hole must be drilled.

Whether an existing hole is chosen or a new hole must be drilled, the Containment Program carefully reviews each proposed site, paying particular attention to the geologic setting, adjacent drill holes, and containment experience in the area. The selection of a suitable depth of burial (DOB) to optimize both containment prospects and use of available test areas is based on these factors.

A containment scientist assigned to each event is responsible for assembling all relevant geologic, geophysical, engineering, historic, and computational information. The containment scientist chooses a final DOB and designs a stemming plan—the plan for filling and plugging the hole after the experiment has been emplaced. The containment scientist prepares the containment prospectus, a comprehensive document that presents all relevant information, expected event phenomena, and justification for the conclusion that the event will be satisfactorily contained. Each event is presented to the Containment Evaluation Panel (CEP), a group of specialists that advises the manager of the Nevada Operations Office of the U.S. Department of Energy on the containment prospectus of every proposed event. No event can proceed unless the CEP concurs with the test sponsor that the likelihood of successful containment is high.

The containment scientist is assisted by an event geologist, an event geophysicist, a containment engineer, and a calculational physicist. The event geologist and geophysicist provide a detailed description of the geologic setting, including the physical properties of the media. The containment engineer assists the containment scientist in designing the stemming plan and is responsible for implementing it in the field. The calculational physicist models the proposed containment design to assist the containment scientist in determining the containment design for the event.

During FY 1989, all events conducted were successfully contained. In addition to preparing LLNL events for the CEP, our containment personnel carefully reviewed the tests proposed by the Los Alamos National Laboratory and the adequacy of their containment designs.

Also, in FY 1989, the Containment Program organized the Fifth Symposium on the Containment of

Underground Nuclear Explosions, held at Mission Research Corporation in Santa Barbara, California, on September 19–21, 1989. Fifty-seven papers were presented, covering research on containment phenomena and related geologic, geophysical, engineering, chemical, and computational topics. Twelve LLNL Containment Program personnel were authors or co-authors on 16 presentations. The proceedings from the symposium are in preparation now at LLNL. This symposium is the only forum for the entire U.S. containment community to discuss the latest research and developments in containment technology and understanding.

Containment Program personnel also have been working on several projects in support of specific test work. Work on these projects is described in more detail in the articles that follow.

Hydroyield Measurements Using Fiber-Optic Techniques

B. C. Hudson

One of the responsibilities of the Containment Program is to provide measurements of hydrodynamic yield for events with design yields of 125 kt or more, or maximum credible yields of 150 kt or more, in conjunction with the Threshold Test Ban Treaty (TTBT). The current technique for measuring these yields is called CORRTX (Continuous Reflectometry for Radius vs Time Experiment). The CORRTX system uses a coaxial cable extending from the detonation region to a recording trailer at the surface. Beginning at zero time, pulses are sent down the cable at intervals of 10 μ s. The system records the round-trip travel time of the pulses from the recording trailer to the end of the cable, which grows shorter as it is destroyed (shorted) by the radially expanding shock wave, and back to the recording trailer. From these measurements, we can derive the yield by determining the shock position vs time.

This system has several shortcomings. First, the signal generated within the coaxial cable often contains information that is classified as secret, but the needed information is only classified as confidential. Second, because this system is normally limited to recording the cable length only once each 10 μ s, the corresponding spatial resolution, depending on the geometry, can be as large as 0.5 m or so. Better spatial resolution is desired for satellite holes. For example, satellite holes are planned for yield verification, as related to the TTBT, to limit access to the emplacement hole as well as to

limit canister effects on the shock time of arrival data. Because the planned separation of a satellite hole from the emplacement hole is normally 10 m or more, the initial shock wave strikes the satellite hole at a rather oblique angle, and "measured" shock velocities near the detonation point level are quite high compared to the "actual" velocities. As a result, the CORRTX sampling rate leads to poor spatial resolution.

A system that uses a fiber-optic cable rather than an electrical coaxial cable could eliminate these shortcomings. Basically, the system

consists of a set of shock sensors for generating light pulses, a fiber-optic cable for transmitting these pulses to the surface recording trailer, and a means for recording these light pulses as a function of time (Figs. 1 and 2). Fiber-optic cables and appropriate recording systems such as digitizers are readily available and relatively inexpensive.

Problems to be overcome include radiation darkening of the fibers, radiation-generated light, and shock-generated light noise. The system we developed consists of quartz "pins" that convert shock

Figure 1. Fiber-optic hydroyield measurement geometry.

Figure 2. Comparison of measured and calculated shock time of arrival. The solid lines represent calculated "strong-shock" curves ($R = at^bw^{(1-b)/3}$, where $a = 6.093$, $b = 0.475$, $t = \text{time}$, and $w = \text{yield}$) using the design yield and the design yield $\pm 10\%$; the triangles represent shock times of arrival as determined from the pins.

energy to voltage; electrical leads long enough to avoid radiation-generated light or darkening within the optical fibers; a means for limiting the signal from a given sensor to a single, well-defined pulse to avoid shock-generated light noise; and a system for multiplexing many signals onto a single optical fiber. The recording system includes an optical sensor and a digitizer. The spatial and temporal resolution are limited by the number of sensors, the accuracy with which the sensors can be located, and the sampling rate of the recording system. In practice, minimum sensor dimensions are on the order of millimeters, and shock speeds are a few millimeters per microsecond. Consequently, an appropriate minimum resolution would be about a millimeter in distance and a tenth of a microsecond in time.

We fielded a system of this type on a recent event. Unfortunately, some cables were broken during device emplacement, and most of the fiber-optic shock experiment was lost. However, the data obtained did confirm that radiation- and shock-induced background noise would be manageable with this system. To provide a "data" background for comparison with the optical data, we also fielded several conventional electrical pins, which detect shock arrival by shorting. The pin data, as illustrated in Fig. 1, provide a feeling for the data quality we might expect from this type of system. The solid lines represent a calculated "strong-shock" curve using the design yield and the design yield $\pm 10\%$; the pin data are shown as triangular points. Fiber-optic hydro-yield systems are planned for emplacement on several future events.

Special Measurements Emplacement System

B. C. Hudson

On an underground nuclear test, special measurements cables and instrumentation must be emplaced so that they will survive the detonation and continue to record plug performance and other containment-related phenomenology well after the event. The best way to ensure their survival is to separate special measurements instrumentation from the main emplacement pipe, thereby decoupling it from the extreme motions associated with the pipe. In the past, this has been done most successfully by preassembling the instrumentation and its associated cables on a wire-rope pendant,

which is lowered into position after emplacing the device. Although we have used this pendant system successfully, it is relatively expensive and time-consuming because it requires significant preparation time in the field before the event, a large area for assembly, and several hours for installation.

We decided to try the special measurements emplacement system (SMES), an adaptation of the cable downhole system (CDS), as a more timely, cost-effective means of emplacing containment-related cables and their associated instrumentation downhole.

History of the CDS

The CDS, an automated, computer-controlled cable emplacement system, was designed to replace the labor-intensive standard method of banding the cables to the main emplacement pipe. The CDS prototype system was used successfully on several underground nuclear tests in the 1980s to emplace most or all of the diagnostics cables. However, as the projections of test demands for the future turned toward fewer but more complex tests with extensive cabling, the potential cost-effectiveness of the CDS and its maintenance infrastructure appeared marginal.

Consequently, its development was discontinued. In FY 1989, some of the CDS components were modified (to eliminate most automated controls) for the Hornitos Event to determine their potential as an improved technique for emplacing only special measurement cables, hence called SMES. The SMES offers the potential of reduced costs and fielding time as well as increased data return.

About the SMES

The basic SMES unit (skid) consists of 10 winches or "tensioners" that control the special measurements cables while lowering them into the emplacement hole (Fig. 1). Tension controls on the skids are wired to remote switches located in a control trailer. An IBM computer, also located in the control trailer, monitors the loads from each tensioner. If these loads exceed predetermined limits during the downhole operation, the computer trips an alarm, and technicians suspend the operation of the tensioner or tensioners indicated until the problem can be remedied.

Before the cables are fed through the tensioners, they are pulled to their expected loads (instrument weight plus cable weight) to measure and mark the cables so that the required emplacement depth can be easily achieved. After the cables are threaded through the tensioners but before they are lowered into the emplacement hole, the special measurements instruments are assembled and attached to the cables. This instrumentation is then manually lowered into position above the emplacement hole, and the cables are placed over two rolling-drum chutes in line with the SMES skid and located directly over the hole (Fig. 2).

The technicians in the control trailer can then use the tensioners to lower the cables and attached

instrumentation into the hole, beginning with the cable containing the instrument to be located at the greatest depth. When the differential between the deepest instrument and the second-deepest instrument is reached, the second instrument is placed on the drum and lowered into the hole at the same rate as the first. This operation is continued until all of the instruments are lowered simultaneously to their final elevations, indicated when the preinstalled markers on the cables reach ground level. The elevations of specific instruments can be fine-tuned by manually operating the appropriate tensioner.

During the downhole operation, technicians continually monitor the loads as displayed on the computer terminal. At the end of each stemming work day, the load readings are manually adjusted to match the instrument weight plus cable weight. After stemming is

completed, the cables are removed from the tensioners and placed over a standard wooden cable chute. The tensioners, rolling-drum chutes, and control trailer can then be removed from the site.

Use of the SMES on the Hornitos Event

For the Hornitos Event, 20 tensioners (two complete skids) were used. They were placed one behind the other at a distance of 200 ft from the emplacement hole. The SMES emplaced six plug evaluation diagnostics (PED) multiplexer systems, each comprising liquid-level conductivity probes, temperature sensors, pressure and radiation gauges, and one stemming canister that held an acceleration gauge and thermistor. The six PED multiplexers were suspended from their individual RF-13 cables, and the stemming canister was suspended from an MP-24 cable.

Figure 1. Skid for the special measurements emplacement system, which contains ten tensioners.

Figure 2. PED instrument system suspended by a cable passing over a rolling-drum cable chute. The sheave and cable in the foreground hold the downhole camera.

In general, the SMES appeared to work well. It allowed the special measurements cables to be emplaced separately from the main emplacement pipe, providing the necessary decoupling to allow the instruments to survive detonation. Emplacement was achieved in a shorter time and using fewer people than are normally necessary. In addition, the system allowed for the retrieval of a PED canister so that a cable connection could be redone. This repair would have been impractical if the instrument had been attached to either the emplacement pipe or a pendant system.

Another problem occurred when an elevation marker was erased, presumably when the cable ran through a tensioner. However, a downhole camera allowed us to position the instrument at its correct elevation.

Our experience on the Hornitos Event showed that the instruments survived the detonation well, and good data were returned. The SMES is now the preferred method for the emplacement of special measurements instrumentation.

Studies of Closure of Noncircular, Off-Axis Lines of Sight

C. W. Olsen

The LLNL has not fielded an underground nuclear test with a long, open line-of-sight (LOS) pipe extending from the nuclear explosion to the surface in more than 20 y. Closure of such a LOS pipe is crucial for successful containment of radioactive debris, but energy inside the pipe can impede such closure. LOS pipes can have considerable energy deposited

within them by direct radiation from the source. Even if much of that energy is blocked by filters or is localized by collimators, considerable energy is deposited in the LOS by ground shock. The shock wave causes symmetric collapse of the LOS pipe resulting in the formation of a jet of hot pipe-wall material. The jet is formed when the material around

the open LOS is shock-loaded and rapidly converges on its axis so vaporized material is jetted ahead of the shock that causes the closure, like a toothpaste tube being squeezed. If the LOS extends much beyond a final cavity radius, particularly if it goes to the surface, prevention of flow in the LOS becomes a containment concern.

We are investigating the behavior of a long, noncircular, off-axis LOS, which could be fielded on a future event. Our studies include two-dimensional computational modeling and small-scale, high-explosive (HE) tests.

Two-Dimensional Computational Modeling

In the computational study, we modeled plasma-jet formation with and without direct radiation into the pipe. The first model simulated a 100-mm-diam, on-axis LOS pipe with prompt radiation into the LOS and a ground shock driven by the thermal environment of the idealized device canister. The second case essentially repeated the first case with the direct-shine energy removed. Both studies showed an early jet with a velocity near 10 cm/ μ s, but the second case had less total energy by about a factor of 2. These calculations were done with the LOS on the calculational axis of symmetry.

To simulate the actual geometry under investigation, we performed calculations with the LOS off axis.

The symmetry of the two-dimensional calculation transformed the off-axis LOS into an annulus surrounding the axis of symmetry. The first baseline calculation simulated an annular LOS with a thin, iron wall and an open-device can embedded in rock of density 2.1 Mg/m³. The geometry was similar to that shown in Fig. 1a but with no tungsten or CH₂. The axis of symmetry is the left side of the figure. The calculated behavior showed some closure across the opening to the LOS, but enough energy was deposited to cause a marked expansion of the pipe rather than its closure. In Fig. 1a, we show another calculation with similar geometry, except mass, in the form of a tungsten sleeve, was added to prevent expansion, and the wall of the canister was modeled to enhance pipe closure. Figure 1b shows the pipe closed at 10 μ s with little jetting. Figure 2 compares velocity in the LOS for the two cases and shows a dramatically reduced flow in the pipe. We performed another calculation similar to the second model, except we added a short, axial LOS to more nearly

approximate an actual canister design. In this calculation, the short, axial LOS displayed rapid expansion and was crushing the annulus ahead of normal ground-shock closure by 100 μ s (Fig. 3).

High-Explosive Testing

We conducted a series of experiments using an HE charge of about 2.1 kg to collapse circular and non-circular plasma generators. Then we diagnosed the resulting flow for various configurations.

Figure 2. Calculated velocities in the annulus at 100 μ s. The first model is the thin-walled LOS and end wall. The second model is shown in Fig. 1a with mass added around the lower part of the LOS. The added mass markedly reduces flow in the pipe.

Figure 1. (a) Initial geometry of annular LOS calculation, and (b) results of calculation at 10 μ s showing closure of the LOS pipe without plasma-jet formation. Density contours are plotted. The axis of symmetry is in the left margin.

Figure 3. Calculation of a combined thin-walled axial and heavy-walled annular LOS pipe. Density contours are at 100 μ s. The axial LOS expands rapidly and crushes the annulus ahead of ground shock.

Figure 4. Layout of high-explosive experiments for the oval-2 test.

Figure 5. Stagnation-pressure data for the rectangular-2 test, showing consistency of data and higher pressures in the middle.

Table 1. Results from high-explosive testing.

Test pipe	Stagnation pressure (kbar)	Velocity ^a (cm/μs)
Round 1	21.0	2.5
Round 2	>30.0	3.4
Oval 1	~3.0	3.3
Oval 2	~2.0	2.6
Rectangular 1	4.4 (center) (symmetric)	3.0 2.1 (sides)
Rectangular 2	2.8 (center) ^b (varied wall thickness)	2.9 1.2 (side)

^a The velocity is dependent on the pressure in the tube, which was not carefully controlled on round-1 and oval-1 preliminary tests. Subsequent tests were conducted at about 0.2 Torr.

^b We measured a static (side-on) pressure of 0.21 kbar.

In Fig. 4, we show the basic experimental layout. The most interesting data derived from these tests are the stagnation pressures found at the end of the tube because these pressures relate to the threat seen by a closure device or other hardware in the pipe. The circular pipes had a single bar gauge that covered most of the pipe's end wall. The oval and rectangular tubes each had three bars at the stagnation end, and, in some cases, each bar had two transducers. Figure 5 shows the stagnation-pressure data for the rectangular-2 test. The internal consistency of the data derived from these experiments was excellent. The oval tubes showed the same stagnation pressure across the end wall, whereas the rectangular tubes (5:1 dimension ratio) showed higher pressures in the center. We summarize the results in Table 1. Qualitatively, the round-tube tests showed significant cratering in the end plug; the asymmetric tests displayed slight ablation but virtually no cratering.

We are continuing to analyze the HE tests and to match the HE experiment data using the same computational techniques as for the nuclear-simulation calculations. Additional effort is needed to incorporate these concepts into an actual canister design.

In summary, we have demonstrated how we achieve potentially large decreases in jet formation and in energy ahead of ground shock in LOS pipes by placing appropriate asymmetries in the close-in portion of a LOS. The reduction in energy in the LOS reduces the threat to closure devices in the pipe and enhances prospects for satisfactory containment of the event.

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