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Physics Division Annual Progress Report

January 1—December 31, 1983

Compiled by
W. J. Trela

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PHYSICS DIVISION ANNUAL PROGRESS REPORT
January 1—December 31, 1983

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ABSTRACT

The Physics Division is organized into three major research areas: Weapons Physics, Inertial Fusion Physics, and Basic Research. In Weapons Physics, new strategic defensive research initiatives were developed in response to President Reagan's speech in May 1983. Significant advances have been made in high-speed diagnostics including electro-optic techniques, fiber-optic systems, and imaging. In Inertial Fusion, the 40-kJ Antares CO₂ laser facility was completed, and the 1- by 1- by 2-m-long large-aperture module amplifier (LAM) was constructed and operated. In Basic Research, our main emphasis was on development of the Weapons Neutron Research (WNR) facility as a world-class pulsed neutron research facility.

EXECUTIVE SUMMARY
J. C. Browne, Physics Division Leader

The Physics Division consists of 14 experimental groups that pursue research and development (R&D) in support of the Laboratory's Weapons Program and Inertial Confinement Fusion Program (see the figure). In addition, a sizable Basic Research Program investigates problems in the forefront of physics in a wide range of areas to provide a strong technology base for current and future Laboratory programs. These activities cover many physics disciplines including plasma physics, atomic physics, nuclear and particle physics, as well as solid-state, condensed matter, and thermal physics. Only a few of the many significant research accomplishments of 1983 are highlighted here.

In Inertial Fusion, the 40-kJ Antares CO₂ laser facility was completed and brought into operation for experiments aimed to improve our understanding of the interaction of 10- μ m laser light with matter. With the completion of Antares, the 5-kJ Helios laser was put on standby operation. Because the laser-matter experiments to date indicate that shorter wavelengths offer more potential for inertial fusion, we are also pursuing a technology demonstration project to investigate 0.25-micron KrF lasers as a low-cost, short-wavelength alternative to CO₂ lasers. We constructed and operated a 1- by 1- by 2-m-long large-aperture module amplifier (LAM) that will produce 10 to 20 kJ of laser light. The LAM is the keystone of a project to test and build prototype hardware for a low-cost baseline 50- to 100-kJ KrF system that will employ angular multiplexing and aperture combination to produce a higher-power short pulse for inertial fusion application.

In Weapons Physics, we began several new strategic defensive research initiatives in response to President Reagan's speech in May 1983. These research initiatives, which build on the strength of the Physics Division in high-energy-density plasma physics, atomic and x-ray physics, and nuclear physics, mesh very well with existing Laboratory and Nevada Test Site programs that are investigating similar physics problems associated with weapons design and performance. There were significant advances in high-speed diagnostics including electro-optic techniques, fiber-optic systems, and imaging during the past year. A major activity is a project to develop beam lines on the X-Ray and VUV Rings at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. This \$4.9M project, which has been funded by the Department of Energy in FY84, will provide important capabilities to the Laboratory for diagnostic development, atomic physics, condensed matter physics, chemistry, and materials science, all of which bear on basic and applied research problems related to national defense.

In Basic Research, the development of the Weapons Neutron Research (WNR) facility as a world-class pulsed neutron research facility continued to be our main emphasis. In particular, condensed matter research using neutron scattering at the WNR facility produced several exciting results that demonstrate the capabilities of the pulsed source. Results include a determination of the structure of ReO₃ via single-crystal diffraction, which demonstrates a compressibility collapse at a pressure of 15 kbar to one-tenth the compressibility at atmospheric pressure.

In Nuclear Physics, significant advances in our weak-interaction program included the development of a neutrino experiment to study neutrino oscillations and neutrino-electron scattering. Exciting results at LAMPF, CERN, and other facilities were also produced in a wide variety of medium- and low-energy nuclear physics experiments. In static high-pressure experiments, several significant results were produced including the production of a polymeric phase of carbon monoxide, at a pressure of 50 kbar, that remains metastable at atmospheric pressure. Our intrinsically irreversible heat-engine research has led to a generalization that applies to many "natural" engines and to a specific application to a liquid-sodium engine that could have a significant application in space nuclear reactor systems.

SPECIAL PROJECTS: PHYSICS DIVISION

Protein Analyzer

H. L. Anderson, Project Leader

We have under development, as a by-product of the time projection chamber technology, an improvement in the means for analyzing the proteins in living cells. The proteins are labeled with ^{14}C or other radioactive materials and then spatially separated by two-dimensional electrophoresis. In this process the proteins are distributed in an array of spots over the surface of a thin layer of gel ~ 20 by 20 cm in area. The proteins are separated by their isoelectric point in one direction and then by molecular weight orthogonally. The location and intensity of the radioactivity in each spot can be made visible by autoradiography. A typical cell species will yield several thousand cells, which must be located and measured in intensity. Although the autoradiographic readout is in wide use, it is relatively crude and tedious to use.

Our electronic readout gives directly the number of β -rays emerging from each spot. It uses a two-dimensional proportional chamber operating in a strong but uniform magnetic field. Because the β -rays from ^{14}C have low energies, about 50 keV on average, they are constrained to move in a tight helix, which keeps close to the magnetic field line that goes through their point of origin. Figure 1 illustrates several such helices in the proportional chamber. We call our device a magnetic projection chamber because of the way it projects the radioactivity from its point of origin into the chamber with unit magnification and good resolution.

The analyzer has been tested using a single small spot of ^{14}C . The resolution, $1500\text{ }\mu\text{m}$ full width at half maximum, is equal to the wire spacing as shown in Fig. 2. This is five times better than when the magnetic field is removed, as shown in Fig. 3.

Fig. 1. Trajectories of representative β -rays with different energies and emission angle in a 1-cm-deep chamber in a magnetic field of 2 T : A, 50 keV , $\cos\theta = 0.3$; B, 25 keV , $\cos\theta = 0.5$; C, 25 keV , $\cos\theta = 0.3$; D, 10 keV , $\cos\theta = 0.5$.

Fig. 2. With a magnetic field of 19,000 G, a small spot of ^{14}C produces a narrow peak, 1500 microns full width at half maximum.

Fig. 3. The same spot without field is five times broader.

Precision Measurement of Muon Decay
H. L. Anderson, Project Leader

The measurement of the positron spectrum of muon decay is one of the most fundamental experiments in particle physics because it is the best way to determine the attributes and magnitudes of the weak interaction. We are making a new measurement with the goal of improving the existing accuracy by a factor of 5. The spectrum can be calculated precisely from the accepted theory, which is based on a simple symmetry proposed by Feynman and Gell-Mann in which the neutrinos are massless with two rather than four components. The only interactions entering are vector and axial vector, of equal magnitude and opposite sign, referred to as V-A. In this theory the currents are left-handed. To date all searches to find right-handed currents or massive neutrinos have been unsuccessful. Because of doubts about the correctness of the result, we discount the Russian experiment that reported a finite neutrino mass. Weak-interaction theory is beautiful in its simplicity, but the purpose of the experiment is to discover whether that beauty is more than skin deep. We plan to measure the spectrum with high resolution and statistics 100-fold greater than previously obtained. We will compare the spectrum with its well-known theoretical value.

We are measuring the spectrum with a novel and newly constructed spectrometer based on the time projection chamber. We use the low-momentum surface muon beam at the Clinton P. Anderson Meson Physics Facility (LAMPF) arranged so that the muons stop in the gas in the middle of the chamber. The spectrometer is capable of high-momentum resolution over a substantial solid angle. It has been operating for more than one year. Figure 4 shows a typical muon decay event.

We recently completed the high-speed data acquisition system needed to collect the larger number of events we require. We are running to test this system and to begin collecting large numbers of events. Several runs are scheduled in winter and spring 1984 for quantity data collection. We are looking forward to our first physics result by the end of 1984.

Fig. 4. A typical event reconstructed from the data. A muon enters the chamber from above, comes to rest near the center, and decays into a position emitted backward. The muon coordinates are marked with the symbol M; the positron coordinates, with the symbol X.

Biomagnetic Field Mapping of Neural Systems
E. R. Flynn, P-DO, and J. George and M. Bitensky, LS-DO, Project Leaders

The program to measure biomagnetic fields from the human brain moved significantly toward an effective and advanced research effort in neural mapping. We completed an extensive data-taking and analysis system using the latest in computer and software techniques. The first completed microcoils are ready for testing. Perhaps the most significant accomplishment was establishing collaborations with several universities and industrial concerns; we also interested several Government agencies in the value of these techniques and the role of the Los Alamos National Laboratory in such research.

A complete data-taking system has evolved around the purchase of a HP 9000 computer using the UNIX operating system. With a CAMAC-based interface through HPIB, we can obtain data transfer rates approaching 1Mb/s. Transient digitizers and DAC units are being used to digitize the output data from the SQUID sensors and to present appropriate visual and auditory stimuli. Software packages using the C-language have been compiled to control all the necessary interface units and to provide graphic presentations in color as well as plotted output. These software routines are being expanded to provide additional data analysis routines for Fourier analysis, source location, and signal conditioning.

Using the photolithography resources of E-Division, we constructed several microcoil first-order planar gradiometers and fabricated a mount for testing these with an rf SQUID. These coils represent a significant achievement in photolithography as they consist of 10 turns of niobium material with 10-micron width and spacing and a total pattern width of only 2 mm. They should lead to a significant reduction in spatial resolving power and will be the initial elements in a full array of SQUID-coupled gradiometers.

To further enhance the use of these microcoils and the entire biomagnetic project as well, we have convinced Sperry Corporation, the leading developer of SQUID technology, to collaborate with us in the development of an advanced array of SQUID sensors. This constitutes another collaboration of Los Alamos with industry. Further collaborations on this project have been reached with Professor Jack Cowan of the University of Chicago who has performed extensive theoretical calculations on brain behavior following distinct visual stimuli. The University of New Mexico has asked to be included in a number of clinical applications when the project reaches that phase. In addition, several DoD and intelligence agencies have expressed their willingness to participate in funding various modes of the biomagnetism.

The variety of studies of the brain and its behavior continues to grow. In addition to the original concept of studying the neural pathways associated with the senses, it is now apparent that the device under fabrication will permit a unique approach to studying the effects of extraneous harmful environments on the nervous system. Other studies are relevant to performance enhancement of military personnel under stressful conditions. There are also significant advantages in the use of magnetoencephalography (MEG) in the field of artificial intelligence, and a project to study the response of the auditory channel to phoneme patterns is under way. In March we will complete the first experiment, which is to measure the response of the visual cortex to light patterns arranged as vertical stripes with a horizontal brightness pattern as a function of a difference of Gaussian distributions.

WEAPONS PHYSICS: GROUPS P-1, P-12, P-14, AND P-15

**F. A. Morse, Associate Division Leader for Weapons Physics
and Deputy Division Leader**

The Weapons Physics groups are responsible for prompt diagnostic measurement of nuclear weapons test devices at NTS, experiments in new weapons concepts, and fundamental weapons physics measurements. The expertise in these groups is also applied to diagnostic development in the laser fusion program and to physics problems in other pure fusion programs. Experimental tasks are characterized by very high-speed measurements of very high-power systems. Characteristic times are 0.1 to 10 ns, and characteristic energies range from megajoules to many terajoules. The experiments require spectrally, temporally, and spatially resolved measurements of x rays, gamma rays, and neutrons.

The effort is divided into four parts: research and development (R&D), experiments, production diagnostics, and analysis/interpretation. With current resources, we are straining to execute eight events per year at NTS and maintain reasonable laboratory R&D. We are emphasizing interpretation to maximize the benefit from each experiment.

Group P-1 is responsible for facets of the fusion project Trailmaster and experimental parts of some weapons projects; P-1 is also responsible for research projects involving a Relativistic Electron Beam (REB) and a Z-pinch apparatus. Group P-12, a mechanical engineering group, supports a variety of projects in the Division. Group P-14 specializes in technological development for application to weapons physics problems and is responsible for fast measurements of gamma rays and x rays in nuclear tests; P-14 has placed special emphasis on x-ray spectroscopy. Group P-15, which specializes in weapons physics, nuclear physics, and neutron measurements during nuclear tests, has successfully developed high-resolution imaging techniques.

The past year brought several interesting tests addressing fundamental weapons physics issues. Principally, we investigated thermal radiation physics in special geometries. We also examined details of the purity of thermonuclear reactions in test devices.

Applications of electro-optic techniques have advanced our diagnostic capability. Our newly developed fiber-optic systems are either less expensive or have greater bandwidths than standard coaxial cable systems. An advance in imaging thermonuclear burn regions promises better understanding of fuel burn and fuel hydrodynamics.

Our measurement capabilities have been successfully applied to other Laboratory programs, particularly the inertial fusion effort. The Trailmaster program to develop high-speed, high-power switches for a magnetocumulative generator has performed experimental tests of two very promising candidates. Progress on new weapon concepts has been outstanding.

High-Energy-Density Physics Group: P-1 Jim Trainor, Group Leader

This experimental physics group is pursuing several investigations in high-energy-density plasma physics. The tools in use are a relativistic electron beam (REB) machine, a cylindrical gas puff Z-pinch system, and a high-current-discharge system. Projects include investigations of beam-driven microwave sources, plasma instabilities, atomic physics at high ionization states (which produce x rays), and an investigation of high-power-switching techniques for use with an explosive-driven magneto-cumulative generator. These are all pulse-power-based projects; most of the work is done with capacitor banks or Marx generators, although some experiments are done jointly with Group M-6 using high-explosive power sources. Group P-1, working closely with Groups P-14, P-15, and M-6, has developed outstanding diagnostic techniques to perform these experiments, several of which are described below.

In the relatively short time this group has been charged with developing these projects, P-1 has produced near-record microwave powers and a working high-power switch experiment, and has shown that Z-pinch gas puff systems are producing plasmas of a few hundred electron volts, not the 1 keV usually ascribed to them.

Nonthermal Electron Effects in Z-Pinch Plasmas

Many recent experiments have examined the plasma conditions produced by a collapsing hollow gas shell Z-pinch. All of these measurements show that the final stage of the pinch is an inhomogeneous column made up of so-called hot spots, which emit line radiation from high-ionization states of the gas (hydrogen-, helium- and lithium-like). The temperature within these hot spots was determined spectroscopically to be ~ 1 keV. Our recent experiments present new spectroscopic evidence demonstrating that an important factor has been overlooked, namely, an energetic electron beam that pervades the plasma at the time of pinch. We also developed a consistent model for the plasma in the presence of this beam and showed that the electron temperature of the hot spots could be as low as 400 eV. If we interpret our data without considering the electron beam, we deduce a peak temperature in these regions of ~ 1 keV; however, we then are unable to explain some of the observed spectral features. In addition, our measurements indicate that other regions of the pinched plasma are relatively cool (~ 270 eV), with an abundance of lower ionization states (beryllium- through fluorine-like).

Although there has been speculation about the existence of a high-energy electron beam at the time of pinch, the effects of such a beam have not been included in the interpretation of any diagnostic measurement. When such effects are included, our analysis shows less than a factor of 2 inhomogeneity in the electron temperature along the axis at the time of pinch, rather than the factor of 4 to 5 previously claimed.

The plasma source used for this experiment was a collapsing hollow argon gas shell Z-pinch. An annulus of gas with a 2.0-cm i.d. and a 2.5-cm o.d. is injected with a line density of $\sim 9 \times 10^{16} \text{ cm}^{-1}$ between two electrodes 1 cm apart with a fast-valve supersonic nozzle combination. A 600-kV Marx bank, which pulse charges a 1- Ω , 90-ns-long water line in ~ 500 ns to a peak voltage of 900 kV, is used to drive the pinch. The gas load is isolated from the voltage appearing on the water line by a gas-filled in-line switch. When peak voltage is reached, the in-line switch breaks down, applying a fast-rising pulse to the gas load (see Fig. 5).

For this experiment the Marx bank charge voltage was ~ 360 kV, which produced a peak voltage in the water transmission line of ~ 580 kV. With this charge voltage, 415 kA were delivered to the gas load with a 200-ns quarter-cycle time at an initial rate of $3 \times 10^{12} \text{ A/s}$.

The observation of a high-energy ($h\nu > 10$ keV) x-ray pulse, which occurs at the time of pinch, triggered earlier speculation that a high-energy electron beam may develop in the final pinch phase of many Z-pinch experiments. We also detect such a pulse in our experiment with the detector shielded in all directions by a minimum of 1-in. of aluminum—thus indicating energies above 1 MeV. These x rays could be produced by energetic electrons, which are accelerated in the pinched plasma, bombarding the

Fig. 5. Schematic diagram of the vacuum discharge chamber and in-line switch.

anode. This explanation is supported by x-ray pinhole pictures taken in our experiments, which indicate that the anode surface is a source of hard x-ray radiation. We also observe the high-energy x-ray pulse when no gas is injected; only in this case, the hard x rays are generated by field-emitted electrons as soon as the in-line switch breaks down, instead of delaying the 200 ns it takes to pinch the hollow gas shell.

The x-ray pinhole picture images of the pinched column in these types of experiments show a bead-like structure along the Z-axis. This structure is assumed to be caused by the onset of the "sausage instability" ($m = 0$), but whatever the cause, it is definitely associated with a large inductive change, $\dot{L}$, at the time of pinch. This large $\dot{L}$ causes a current interruption and hence a large voltage spike, which occurs at the time of pinch,

$$V = \frac{d}{dt} (IL) .$$

This voltage spike can accelerate electrons to high energies, leading to the hard x-ray emission. We also have observed this bead-like structure in the soft x-ray pinhole pictures and, in fact, see that it is correlated with the hard x-ray emission. (In one operating condition, the hard x-ray pulse is not observed, and no image is seen on the x-ray pinhole pictures.)

We have obtained further evidence for the presence of a high-energy electron beam by spectroscopic means. The x-ray spectrum was dispersed using a curved germanium (111) crystal. The spectrograph was used in the slitless mode with a beryllium filter blocking the low-energy photons. A scan of the spectrum, recorded on Kodak 35-mm no-screen x-ray film, is presented in Fig. 6; the helium-like argon resonance and intercombination lines are easily identified. To the low-energy side of these lines are six weaker structures. We identified these transitions as being due to the relaxation of the excited state caused by inner shell excitation of the l-s electron argon XI to argon XVI. Calculations carried out with an atomic physics code¹ and convolved with our instrument function are consistent with this identification and are also shown in Fig. 6.

These satellite lines are inconsistent with what we expect from a thermal plasma, because the excitation energy (~ 3 keV) is much greater than the temperature at which these low ionization states are present (200 to 300 eV). Electrons with energies above the excitation energy of the observed transitions that stream through a cool plasma, could, however, create these transitions. A simple estimate, using the collisional excitation cross section for these transitions, indicates that a beam of energetic (~ 4 keV) electrons, which carries less than 10% of the total peak current, could produce the observed spectral intensities. Satellite transitions from inner shell excitation have been observed in other similar experiments where superthermal electrons are produced.^{2,3}

After establishing the existence of a high-energy electron beam at the time of pinch, we must develop a model that includes the effects of this beam and is consistent with all the observations. The model that fits this criterion is that as the plasma compresses, the sausage instability causes an inhomogeneous

Fig. 6. A comparison of the observed x-ray spectrum with the calculated inner shell vacancy spectrum of Cowan.¹ The dashed line represents a 10X scale change.

column with some regions of slightly higher electron density and temperature than others. This hypothesis is supported by the axially and radially imaged time-integrated vacuum ultraviolet (VUV) spectra shown in Fig. 7. From the radially imaged spectrum, which averages over the central 0.75 cm of the plasma column, we observe that argon XIII to argon XIV are emitted when the plasma is compressed to a diameter of less than a millimeter. In addition, low ionization states of argon (X to XII) occur when the plasma is less compressed (diameter ~ 4 mm) as well as on the axis. Because shadowgrams taken at the time of pinch show discharge column diameters of ~ 1 mm, which are nearly always straight, we concluded that the larger radial extent of the argon X to argon XII lines is due to the time evolution of the plasma. The axially imaged spectrum shows a strong anticorrelation of the emission by argon XIII and argon XIV excluded from the spectral range of Fig. 7) with the x-ray pinhole image that represents primarily argon XVII, indicating that some regions are hotter than others. A collisional radiative model indicates that argon XIII to argon XIV are abundant at a temperature of ~ 270 eV; however, at 400 eV these low ionization states are "burned out," creating argon XVI and argon XVII. The satellite lines, discussed in the previous section, can be produced in the cool regions by nonthermal electrons, which are accelerated in the pinched plasma.

If the plasma is assumed to be thermal, the hydrogen-like to helium-like line ratio yields an electron temperature in the hot spots of 1 keV at the time of pinch. If an energetic electron beam is included in the interpretation, however, the thermal plasma does not have to be hot enough to excite the 3-keV

Fig. 7. (a) Axially imaged vacuum ultraviolet (VUV) spectrum compared to x-ray pinhole picture taken in the 1 to 5 keV region. Both images display the entire 1-cm gap between the electrodes. (b) Radially imaged VUV spectrum. These images average over the central 0.75 cm of the plasma column.

levels of the helium-like argon; it need only be hot enough to generate a large quantity of ground state argon XVII. As the collisional excitation cross section for all of the observed x-ray lines is approximately the same, the energetic electron current required to explain the existence of the satellite lines in the cool regions of the plasma is also adequate to produce the observed intensity of the helium-like resonance line from the hot spots. In addition, a simple estimate of the collisional ionization cross section indicates that such a beam can produce a sufficient amount of helium-like argon to produce the observed ratio of the helium- and hydrogen-like resonance lines. Thus a plasma thermal temperature of <400 eV and an energetic, $E \approx 4$ keV, electron beam that carries less than 10 per cent of the total current are sufficient to produce all of the observed x-ray transitions.

Another means of estimating the temperature has been to use the ratio of the so-called dielectronic satellite line with the helium-like argon resonance line. This produces an estimated temperature of ~ 1 keV in most collapsing shell Z-pinch. The argument that the observed satellite line is due to dielectronic recombination is valid only for a thermal plasma. When an energetic electron beam is present, the total rate for inner shell ionization can be larger than the dielectronic recombination rate because the latter is a resonant process whereas the former is a continuum process. All electrons with energies greater than or equal to the excitation energy can contribute.

We have shown experimental evidence for the existence of an energetic electron beam at the time of pinch in a collapsing hollow gas shell Z-pinch. We have also shown that including the effects of an energetic electron beam in the plasma modeling can reduce the deduced temperature by over a factor of 2. Experiments are continuing to measure the current and energy of the above-mentioned beam.

Physics of High-Power Microwave Generation

We have embarked on a new program to investigate the generation of extremely high-power microwave radiation using the unique properties of the Group P-1 intense relativistic electron beam. In the last several months we focused our effort on devices that exploit the formation of virtual cathodes to produce high-power microwaves. Such devices, which heretofore received only sporadic attention, have some very attractive features that include simplicity, operation at very high current levels because beam propagation is not required, and operation without slow wave structures—which are subject to microwave breakdown.

Virtual cathode formation (Fig. 8) occurs when an electron beam carries so much current that it cannot fully propagate in the drift region downstream of the diode. The beam transport is inhibited by its own electric fields that come from beam space-charge and allow only part of the current to flow. The

Fig. 8. Experimental configuration.

remaining portion of the beam is reflected back into the diode region. The reflection point is the position of the virtual cathode. For an axisymmetric beam, the space-charge-limiting current above which a virtual cathode forms is given by the relation,

$$I_{sc1} = \frac{17,000 (\gamma^{2/3} - 1)^{3/2}}{\delta + 2 \ln (b/a)} \text{ amperes} ,$$

where γ = relativistic factor, b/a = wall radius/beam radius, $\delta = 1$ for a uniform current density, and $\delta = 0$ for a thin annular beam.

Two processes have been identified that can lead to the production of high-power microwaves when the space-charge-limiting current is exceeded. In the first, the oscillating virtual cathode or Vircator mechanism, both the amplitude and the position of the virtual cathode oscillate, leading to heavy modulation of the transmitted portion of the beam current (that is, the virtual cathode acts as a gate, chopping the beam current). These charge bunches in turn strongly excite axisymmetric transverse-magnetic waveguide modes. The oscillation frequency varies from $\omega_p/2\pi$ to $\omega_p/\sqrt{2}\pi$, depending on the ratio of the injected current to the space-charge-limiting current; here $\omega_p/2\pi$ is the relativistic plasma frequency [that is, $\omega_p^2 = (4\pi N_e e^2/\gamma m)$].

In the second process, the reflex mode, the electrons reflex between the real cathode and the virtual cathode, forming coherent bunches of charge in the process. This phase bunching, which is similar to the bunching that occurs in a gyrotron, results from the energy dependence of the electron relativistic mass. Again axisymmetric transverse-magnetic waveguide modes are excited. The generation process that dominates in a given device is a subject of current research but appears to be sensitive to the beam-to-waveguide radius ration.

For our beam parameters ($V \sim 3$ MV, $I = 50$ to 100 kA), computer modeling indicates that power output levels on the order of 10 GW in a frequency band from 10 to 30 GHz should be obtainable with a peak efficiency of about 10 per cent.*

Fig. 8 shows the experimental arrangement. Typically the beam electrons are emitted from a 2-cm-diameter cathode (0.05-cm wall thickness) centered inside a 3.6-cm-diameter graphite tube at ground potential. A thin, aluminized plastic foil (highly transparent to beam electrons) positioned 0.5 to 1.0 cm from the cathode end serves as the anode. Downstream of the diode the microwaves are transported along a 1.1-m length of circular waveguide (diameters from 6 cm to 20 cm are being investigated) to allow a region for spent electrons to harmlessly diverge to the tube walls. The waveguide is followed by a 1.1-m-long conical antenna, which is terminated by a 0.6-m-diameter vacuum window that is large enough to avoid microwave breakdown at the vacuum-air interface.

The microwave signals are detected by an array of microwave receivers located 2.5 m from the vacuum window. Frequency coverage, at present, is from 2 to 40 GHz with waveguide dispersion and bandpass filters for frequency measurements. Most structure is measured primarily by making shot-to-shot scans of the radiation field and by observing the light output from an array of fluorescent tubes illuminated by the microwaves. A microwave calorimeter of novel design is currently being developed to make accurate power measurements.

Initial results were obtained using a configuration employing a 6-cm-diameter waveguide. Preliminary observations are summarized as follows:

- The strongest signals are observed in the waveguide channels from 8.0 to 40.0 GHz, depending on the particular diode configuration.
- When operating with a large (~ 1 -cm) anode-cathode gap, the output frequencies occur near the cutoff frequencies of the cylindrically symmetric transverse-magnetic modes of the drift tube.
- As the anode-cathode spacing is reduced, leading to increased beam current and probably increased current density, the output frequencies shift to the higher bands.
- Radial mode patterns were determined on a few shots ~ 2.0 -m downstream from the output window. The mode structure and frequencies appear to be consistent with our understanding that TM modes near cutoff are excited.

*Information provided by T. J. T. Kwan, Group X-8, Los Alamos National Laboratory, 1984.

- Very crude power estimates were made for the most recent shots with an anode-cathode spacing of ~ 0.6 cm. The major difficulty arises from estimating the microwave field structure in the near-field region of the output window. We saw many tens of megawatts at the low end of K-band (~ 18 GHz) and ~ 10 MW at the high end of Ka-band (~ 35 to 40 GHz). Refinement of power measurements is a continuing activity.

We soon will be evaluating two larger-diameter drift regions, as increased waveguide diameter has been observed to greatly enhance output power in a similar AFWL experiment. Future plans also include

- Magnetized diode virtual cathode microwave generation.
- Finite-length interaction with a partially reflecting boundary along the axis.
- Alternative power extraction configurations to avoid the high-order transverse magnetic modes and the large-diameter output window.

We are investigating other microwave generation techniques that can take advantage of the unique properties of the Los Alamos REB facility when operated in the magnetized-diode configuration (for example, well-confined, low-divergence, high-brightness beam).

Laser Scattering from an Intense Relativistic Electron Beam

The scattering of laser radiation from plasmas has come into widespread use in recent years. One of the most powerful diagnostic techniques at the disposal of plasma experimentalists, laser scattering allows nonintrusive spatially and temporally resolved measurements of electron density and temperature and yields a wealth of information about turbulent plasma behavior. In contrast, no similar diagnostic technique has been exploited in intense electron beam research in spite of the absence of good, nonperturbing diagnostic methods.

Initial experiments have tested the feasibility of using inverse Compton scattering of CO_2 laser radiation from an intense relativistic electron beam to measure various beam parameters, such as beam energy and divergence. Inverse Compton scattering is the process in which a low-energy photon collides with a high-energy electron with the recoil photon gaining energy from the electron (in contrast to Compton scattering where a high-energy photon imparts energy to a stationary electron with the scattered photon losing energy). The recoil photons are confined to a cone aligned along the beam direction having a half-angle given by $1/\gamma$ (γ is the relativistic factor). The photon energy gain is $2\gamma^2$ for 90° scattering (that is, where the incident photons are at right angles to the beam direction). Thus, for $10.6\text{-}\mu\text{m}$ CO_2 radiation and $2.5 < \gamma < 4.5$, as in our case, the scattered signal is in the visible and near-ultraviolet portions of the spectrum.

Figure 9 shows the experimental arrangement. A 10-J CO_2 laser pulse, which is 60 ns in duration and consists of a train of subnanosecond pulses, is incident at nearly 90° to a 1.5-MeV, 30-kA relativistic

Fig. 9. Inverse Compton scattering experimental configuration.

electron beam that is 50 ns in duration. The electron beam generated in a magnetized foilless diode has a 0.1-mm-thick annular cross section with a radius of 1 cm. The scattered radiation that emerges from the target chamber through a thin 150- μ m plastic vacuum window (which minimizes Cerenkov radiation from stray electrons) is collected at an angle slightly off of the electron-beam direction to avoid gathering plasma light produced in the diode. The scattered light is relayed and focused onto the input slit of a 1/4 m spectrometer by a mirror-lens system. The output of the spectrometer is coupled by means of fiber-optics to four photomultiplier tubes (RCA 8644), which are heavily shielded from EMP and stray magnetic fields by a copper box. The entire detector system is surrounded by a massive two-ton lead shield to reduce to an acceptable level the x-ray signal generated by the spurious beam. Furthermore, the graphite electron-beam stop has additional lead shielding around it to shadow the detectors. In all of the experimental observations, the pressure in the target chamber is lower than 5×10^{-5} torr.

Figure 10 shows oscilloscope traces of two photomultiplier-tube output signals, one with and one without the laser incident on the electron beam. The upper trace corresponds to a spectrometer wavelength setting of 4400 ± 17 Å; the lower, to a wavelength setting of 4246 ± 17 Å. When the laser is used, large narrow spikes, corresponding to the scattered signal, are observed clearly on the traces at the time of peak machine voltage. Therefore we infer that the peak gamma is equal to 4.1 ± 0.2 , which is in excellent agreement with the beam energy measured by the usual voltage monitor when corrections are made for the electron-beam self-electric field.

At present the laser bandwidth has been narrowed by the insertion of a diffraction grating in the laser cavity. With this modification, we will soon measure beam divergence by measuring the spectral width of the scattered light.

High-Energy Foil Implosion Experiments

The goal of the Los Alamos imploding foil project is to develop an intense source of soft x rays and hot plasma for fusion and materials properties experiments. With a planned delivered energy of several megajoules on a time scale of ~ 10 ns, this source would far exceed the power capabilities of existing high-power lasers and pulsed-power machines. Our approach uses the high electrical energy produced by a magnetic flux compression generator to implode a thin foil in Z-pinch geometry. The project is a collaboration among several Laboratory divisions; P-Division has three responsibilities: to develop a switch to transfer multimegampere currents from the flux compression generator to the imploding foil load on a submicrosecond timescale, to understand the physics of power flow under the extreme conditions of magnetic fields near 1 MG and electric fields of several hundred kilovolts per centimeter, and to provide a diagnosis of the imploding foil.

Fig. 10. Oscilloscope traces of photomultiplier output signals with and without the laser beam incident on the electron beam.

In this report we describe progress on development of an appropriate opening switch, which we presently regard as the key component in the fielding of a successful implosion experiment. The purpose of the opening switch is to compress the nominal 10- μ s generator output pulse to the duration of the few hundred nanoseconds required to efficiently drive a foil implosion. In operation, the switch is to remain closed for ~ 10 μ s in a circuit containing the generator while current increases and energy is inductively stored. Near peak current (50 to 100 MA), the switch must open quickly (>0.3 μ s) and divert the current into a second inductively matched circuit containing the foil load. This time scale is dictated by the necessity to inhibit deleterious instability growth and power flow failure. Each of the two switch types discussed here has already demonstrated efficient submicrosecond switching under conditions similar to those expected in a full-scale generator-driven experiment.

Opening switch experiments were performed on a 0.6-MJ capacitor bank, configured to deliver peak currents of 5 MA to a shorted load with a 6- μ s risetime. The physics of switch operation was studied using a comprehensive array of diagnostics; included were Rogowski loops and Faraday rotation probes for current diagnosis; a voltage probe to measure switch impedance; pulsed-laser schlieren and fast-framing camera imaging to characterize mass flow and emission history; fiber-optics detectors to measure switching foil velocity; and temperature measurements including a time-resolved visible spectrograph, an x-ray diode, and a uv spectrometer.

We are studying vacuum integral switches, which are integral parts of the vacuum transmission line and have no separate storage inductor or insulator associated with them. We discuss first the magnetic gate proposed by Steinberg and Shearer at LLNL for operation in xenon gas. The gate is a slab of material with its mass thinned along its center and is positioned as an electrical short in the transmission line. The gate is joule-heated by the current passing through it. As the magnetic field pressure increases with the current, the gate material loses its mechanical strength and begins to flow plastically. With slow rising currents the formation of shocks is not a significant effect. About 90 per cent of the gate material is deposited on the surface of the transmission line. This material is pushed to the electrodes, much as a gate opens, with plastically flowing hinges. The remaining material, which continues to carry the current, is thinned as the gate opens; thus the rate of Joule-heating increases rapidly. The material quickly forms a conducting sheath and is accelerated down the transmission line by the $\mathbf{J} \times \mathbf{B}$ force. It passes over a slot in the line, which represents an alternate path for the current, that is, a region where a load would be located. The switching time is determined by the sheath velocity and its thickness. Figure 11 shows the experimental configuration.

The switch shown in Fig. 11 was tested in planar geometry to improve diagnostic access and to minimize the effects of magnetic field gradients while operating at large peak fields. The gate was designed using two simple criteria. One, the entire gate should yield and begin to flow plastically at the same time. This is done to form a plastic hinge at the points where the gate attaches to the electrodes, the points of maximum bending moment, and to prevent the gate from shearing off at these points and accelerating as a unit down the transmission line. The gate flows open and deposits the bulk of its material on the electrode. The mass-thinned region is probably the source of the material that is

Fig. 11. Magnetic gate switch in planar configuration.

accelerated and performs the current transfer. The gate should also yield early in the rising current pulse, thus allowing time for the bulk of gate material to flow to the electrodes and for the sheath to form in the rising part of the current pulse.

Multiple switching slots with current probes in each slot were used to follow the progress of the sheath and directly measure the current transferred to each slot in the experiments. The current delivered to the gate was measured by a probe less than 1 cm away. Redundant current measurements were provided by Rogowski loops and single-mode optical fiber Faraday current probes, fielded by Group P-14.

Figure 12 shows the current versus time for a multiple-slot experiment. These data are typical of the operation of the magnetic gate. Only minor shot-to-shot variations have been seen for the same operational conditions in the 10 shots studied. Current is transferred to the slots at different times consistent with the theory of operation mentioned earlier. Discrepancies in the magnitude of the currents are representative of experimental uncertainties. The relative timing is known to ± 50 ns. In the first slot the switching time (0 to 100 per cent) is $1.5 \mu\text{s}$ starting at $6.3 \mu\text{s}$; in the second slot it is $1.1 \mu\text{s}$ at $7.8 \mu\text{s}$ into the current pulse. A third probe in a third slot failed at $8.1 \mu\text{s}$.

The switching time data were analyzed with a modified $F = ma$ model. We assumed that the sheath was accelerated by the full current flowing in the system and that the sheath mass remained constant as it progressed down the line. The result of this calculation is shown in Fig. 13. The calculated results are consistent with about 5% of the original gate mass reaching the diagnostic slots. For comparison a calculation for acceleration of the entire gate mass is shown. Calculated positions, velocities, and sheath thicknesses are consistent with the framing camera and laser shadowgraph data.

Of the 200 kJ of energy stored in the capacitor bank, less than 5% is consumed by the gate in kinetic energy, thermal energy, and radiation. In addition, the excellent agreement of the delivered current and switched current for times after switching indicates that restrike does not occur during the time of interest.

Fig. 12. Current profile from test of magnetic gate switch.

Fig. 13. Comparison of experimental data and calculations for the magnetic gate switch.

The second switch type we studied is a moving-foil switch. Its operation is similar in principle to a rail gun. The moving-foil switch, shown schematically in Fig. 14(a), magnetically accelerates a thin aluminum foil in coaxial geometry to a high velocity ($\sim 10^6$ cm/s) and then allows it to cross a gap that contains the foil load. The current carried by the foil is switched into the gap in approximately the foil transit time across the gap. Figure 14(b) shows results typical of our first series of experiments with the moving-foil design. About 70% of the 2-MA maximum current delivered to the foil was switched into a diagnostic current gap with a 10 to 90% risetime of <1 μ s. The current density in this case was about 0.8 MA/cm, close to that expected realistically from an explosive generator. A maximum foil velocity of 0.5 cm/ μ s was inferred from the measured arrival time at the gap.

In summary, we have demonstrated the vacuum performance of two fast-opening switches. Sub-microsecond opening times have been measured in the presence of near megagauss magnetic fields. Both switches are prime candidates for full-scale generator-driven tests in the coming year.

Experimental Support: Group P-12
W. O. Miller, Group Leader

Group P-12 provides mechanical engineering expertise to P-Division. The group designs precision optical mounts, remote positioning devices, complex structures, and pressure vessels and is highly skilled in finite element methods to support general structural analysis as well as in dynamic response studies. The large finite element model (FEM) structural codes operate interactively on a VAX-based computer system, which we use for our computer-aided-design (CAD/CAM) operations. Our CAD/CAM system is used in the design of our weapon physics diagnostics projects, in our ICF project, and for other design tasks involving complex three-dimensional bodies.

Figure 15 is a photograph of the Antares target at the instant the Antares Laser Fusion Facility delivered energy from 24 laser beams of carbon dioxide light onto a plastic-covered, gold-plated, copper sphere. This milestone, the culmination of P-12's extensive mechanical engineering activities for Antares, is noteworthy because the 24 optical beams travel over 90 m from the power amplifier before focusing onto the target. Alignments on the order of ± 45 μ m were achieved. Group P-12 was responsible for all mechanical design including the optical-mechanical design of essentially all elements in the beam train. We are gratified to learn that the system exceeds our original design expectations. The

Fig. 14. Moving-foil switch. (a) The experimental configuration. (b) Measured currents delivered to the switching foil and transferred to a switching slot by a moving-foil switch.

Fig. 15. The first visual evidence that the world's largest carbon dioxide laser, at Los Alamos National Laboratory, can deliver power on-target. A plastic-covered, gold-plated, copper sphere as small as the head of a thumbtack was struck by 10 trillion W of power when all 24 beams of the Antares system were trained on the target simultaneously, Tuesday, December 27. The resulting "star" is the glow of hot gases and debris caused as the target vaporized. Antares, still in the preliminary testing stages, will be used to study the basic physics involved in producing laser fusion. Tests using targets barely visible to the human eye and filled with deuterium and tritium are expected to begin in early 1984. The photo was taken by a camera mounted in a port on the target chamber.

operations team can complete several days of test without realignment of the entire system. Shot-to-shot realignment within the power amplifier is correctable through realignment of one element in each beam line. Evaluation of the target system optical stability is continuing.

Our staff provided major support to the krypton fluoride (KrF) laser project, Antares, WNR upgrade, and Heavy-Ion Injector project over the past year. More recently we have been engaged in the detailed design of the Brookhaven National Laboratory spectroscopy beamline for P-14.

Six designer engineers from Group P-12 were cited as worthy of the award for "Best Use of Materials and Fabrication Processes" by *Materials Engineering* in 1983. This award placed Group P-12 in the "Top Twenty Award of Excellence" category with *Materials Engineering*.

Fast Transient Plasma Measurements: Group P-14
Peter B. Lyons, Group Leader

Group P-14 investigates the physical parameters of high-density, high-temperature plasmas emphasizing measurements that require documentation of fast transient electrical and optical signals. Most of the group's efforts concentrate on weapon physics—measurements of gamma and x rays from nuclear devices at the Nevada Test Site (NTS). However, Group P-14 also supports similar measurements on Laboratory sources with similar plasma conditions, such as ICF or imploding-foil studies. Technology development to support these diagnostic measurements is strongly emphasized. Basic research is conducted in neutrino physics at LAMPF and in anomalous emissions in Z-pinch plasmas.

Particular strengths within Group P-14 include state-of-the-art x-ray diagnostic and calibration expertise, high-bandwidth instrumentation, data analysis and processing, and electro-optic technology, particularly fiber optics. Group P-14 is active in studies of several advanced concepts of interest in Laboratory programs for Strategic Defense Research.

Advanced Gamma-Ray Diagnostics

This year we fielded our first effort to isolate the 16.7-MeV gamma ray produced in the $d + t$ reaction. The $d + t$ reaction, the main thermonuclear fusion reaction in many systems, is usually regarded only as a source of 14-MeV neutrons. However, a gamma-ray branch of the reaction has been documented in the literature, with large uncertainty on the branching ratio (10^{-4} to 10^{-5} in different studies).

In many systems the reaction rate for $d + t$ is of major importance. Although the 14-MeV neutrons provide a clear diagnostic for this reaction, these neutrons suffer time-of-flight dispersion and cannot provide an unambiguous measure of the reaction rate. The 16.7-MeV gamma rays, in contrast, are a direct measure of this rate.

We evaluated many technologies for detection of such a weak signal in the presence of copious neutrons and lower-energy gamma rays. We elected to use two techniques for a first attempt at this measurement: a magnetic, 180° deflection, Compton spectrometer and a combination of a gas Cerenkov detector with a magnetic deflection system. Both systems returned excellent data.

The 180° Compton spectrometer was carefully calibrated with electrons at our electron linac at EG&G, Inc., Santa Barbara. That system returned the data of Fig. 16, definitely confirming detection of the 16.7-MeV gamma ray.

The gas Cerenkov detectors used low-pressure gas to establish a threshold for Cerenkov production in the 10- to 14-MeV electron energy range, depending on the particular channel. Only Compton electrons

Fig. 16. Magnetic spectrometer data.

above the threshold could generate Cerenkov light. We established a goal for this instrument to provide six decades of rejection in sensitivity between fission gamma rays and the 16.7-MeV gamma ray. To achieve this superb rejection efficiency, we incorporated a magnetic deflector for Compton electrons before the electrons entered the gas volume. We achieved the six-decade goal with sensitivity curves like those of Fig. 17. Our data confirmed a branching ratio of 9×10^{-5} ($\pm 30\%$).

Having documented the ability to detect and record this weak gamma ray, we are now developing several related technologies. In particular, we are investigating a system to permit time and space resolution of this gamma ray.

Fiber-Optic Technology

Fiber-optic technology offers significant advantages in weapons test diagnostics. Not only are optical fibers less expensive than coaxial cable, but fibers also have much higher bandwidths. We expect that, in a few years, fibers will replace cable as data transmission lines at NTS. Fiber optics are now used in several of our diagnostic systems, and we are developing the requisite technologies to expand our utilization.

High-bandwidth gamma-ray diagnostics use the Cerenkov effect directly in optical fibers. We demonstrated a system response of 220 ps over kilometer-length fibers, but this response time is limited by the speed of our best photomultipliers. We designed and tested the prototype of a system that couples this Cerenkov signal into a streak camera whose bandwidth far surpasses that of any photomultiplier. We incorporate into this system an optical delay, varying with wavelength, to compensate for material dispersion in the optical fiber. This will allow us to utilize most of the available bandwidth of the fiber and streak camera. We recently demonstrated a 400-m fiber and streak system with a 92-ps response time to an 80-ps laser input.

Fig. 17. Sensitivity of a system consisting of magnetic deflection of electrons and a gas Cerenkov threshold detector. Note the six-decade rejection of low-energy electrons.

In a collaborative venture with MIT Lincoln Labs, we are studying Mach-Zehnder interferometers for fiber-optic applications. These integrated-optic devices, shown schematically in Fig. 18(a), split an optical input into two single-mode planar waveguides in a lithium niobate substrate. A voltage provides an electric field across one of the waveguides, inducing a phase change proportional to the voltage. The two waveguides then are recombined providing an output intensity proportional to $\sin^2 kV$, as shown in Fig. 18(b). We envision applications wherein an electrical signal is generated and coupled into the phase modulator section. An optical fiber would carry the modulated light to a remote detector. We tested these devices extensively this year by comparing an electrical drive (simultaneously recorded on an oscilloscope) with a reconstruction of that drive from the interferometer output signal. Figure 18(c) shows the excellence of this agreement; the two representations of the drive are virtually indistinguishable. We emphasized such comparisons at increasing voltages to determine the field level at

Fig. 18. (a) Schematic representation of Mach-Zehnder interferometer geometry. (b) Output of the interferometer as a function of input voltage. The voltage for $1/2$ cycle is V_π , which is of the order of 1 V for some of our modulators. (c) Overlay of Mach-Zehnder modulator and driving source time histories. The curves are indistinguishable over the range shown here, illustrating the excellent performance of the modulator.

which the first-order electro-optic effect in lithium niobate is complicated by higher order terms. Up to voltages of 160 V, we have yet to find any nonlinearity. Further development of these devices should lead to field tests next year. Present models are of moderate, 200-MHz, bandwidth due to a simple electrode construction, but we are actively pursuing better designs that should readily exceed 3-GHz bandwidth.

Most of the data transmission needs of Groups P-14 and P-15 at the Test Site are satisfied with 200-MHz bandwidth. Group P-14 developed, jointly with Group P-15, a set of specifications for an optical data link that could be used as a cost-effective replacement for the majority of the coaxial cable at the NTS. This year we concentrated our efforts on collaboration with industrial organizations, development of link characterization technology, and low-noise front-end receiver designs, with substantial progress in all areas. The characterization techniques emphasized measurements of intermodulation distortion, which require injection of two pure sine waves into the transmitter and measurement of the amplitude of the difference frequency. This technique allows all three frequencies (two inputs and the difference output) to be within the passband of the overall link. (Simpler tests with a single sine wave with observation of harmonics cannot stay within the passband and still test the link over its full frequency range.) We calculate that a demand for a 1% linearity translates to intermodulation distortion (IMD) that is 46 dB below the input. Data from our best link design are shown in Fig. 19, with IMD of -45 dB and excellent pulse response. We fielded this link once to test its electromagnetic interference (EMI) performance downhole; we had very favorable results.

In many of our past experiments, we sampled and transferred images by coherent optical fiber bundles. This year, however, we demonstrated an exciting new technology for image transfer. We successfully transmitted a *two*-dimensional image on a *one*-dimensional fiber array, thereby reducing fiber number and complexity by a very large factor. The system, wavelength-encoded image transmission, relies on a linear fiber array to provide sampling in one dimension and wavelength encoding in the other dimension. A grating is used to disperse the various wavelengths emitted from each image point. The image information is then encoded by the particular fiber in one dimension and by a particular wavelength in the other dimension. The system was successfully tested after extensive study and mockups at EG&G, Inc., in Santa Barbara. This first system transmitted the image for about 10 m, but kilometer distances are possible with development of appropriate scintillators.

Measurement of large pulsed currents presents serious technological challenges. Conventional electrical measurements are complicated by serious EMI concerns near pulsed, multimegampere current sources. We continued to develop fiber-optic Faraday rotation sensors that provide an all-dielectric sensing capability. These systems rely on rotation of the plane of polarization of laser light in single-mode fibers that loop around a generator load. Measurements on explosively driven flux compression generators are now routinely made; Fig. 20 shows data from one such test with a peak current near 10 MA. Other tests were diagnosed with currents over 50 MA.

Fig. 19. Link performance with 1 km of fiber. (a) Step response of link. (b) Intermodulation distortion, at 20 MHz, observed with injection of two pure sine waves at 190 and 210 MHz.

Fig. 20. The upper curve is an oscilloscope trace showing the transmission of polarized 803-nm light from a single-mode optical fiber through a polarization analyzer. As the generator load current increases, the induced magnetic field rotates the polarization ($163^\circ/\text{MA}$) of the light in the fiber. The lower curve shows the detected current as a function of time.

Fast Transient Measurements

Fast (high-bandwidth), transient (nonrepetitive) measurements of x and gamma rays are required in both the Weapons and the Inertial Fusion programs. Such measurements present unique technological problems that Group P-14 has addressed very effectively.

Whether optical or electrical, fast signals must be recorded on suitable instruments. We emphasize oscilloscopes and streak cameras as the two most promising technologies. We are producing at Los Alamos a high-bandwidth oscilloscope using a commercial CRT tube that was developed through an industrial cooperation program. Through our EG&G, Inc., support facilities, another oscilloscope that is optimized for our reaction history requirements is now in production. The latter scope is being designed to allow microprocessor control of most operations. In our industrial collaboration program we are actively studying improved deflector systems for a future generation of CRTs.

Our interest in high-bandwidth technology requires that we support state-of-the-art efforts in many aspects of optical and electrical technology. Historically, amplifiers were a serious limitation in such measurements. As the technology of GaAs discrete components has rapidly evolved, high-bandwidth amplifiers have become possible. We successfully built and characterized a 4-GHz power amplifier using GaAs FET devices. The unit demonstrated a gain of 5 with a 20-V output. However, at present, all GaAs devices demonstrate a low-frequency instability that precludes amplifiers with response to dc. We participate in an industrial collaboration that seeks to understand and avoid this instability.

Coaxial cables always represented a serious limitation on realization of high-bandwidth electrical systems. Over the years, we developed many techniques to equalize coaxial cables, thereby improving their frequency response. Our previous technologies allowed us to provide bandwidths to 500 MHz over long cables. Studies this year concentrated on improved measurement and modeling of the properties of coaxial cables and on new architectures for equalizer characterization and fabrication. This led us to new designs for reflective equalizers using distributed, instead of discrete, components, with excellent results at frequencies up to 5 GHz. Capable of holding off 4 kV for 300 ns, the new designs were used on NTS events. We fielded long coaxial lines with bandwidths over 1.5 GHz this year and anticipate lines over 2 GHz on future tests.

For some systems even 2-GHz data may be insufficient, and we are investigating approaches for measurements in the 2- to 8-GHz range. One approach involves a discrete spectrum analyzer consisting of a series of tuned narrow-band filters to document the Fourier amplitudes of selected frequency components. Phase information is not recorded but has been estimated by the Bode phase integral (or

Hilbert transform). Thus far we have completed several computer modeling exercises using eight bandpass filters (from 0.2 to 8 GHz) to sample the input signals. We recovered eight samples of the input signal power spectrum, each located at the resonant frequency of its respective filter. Comparison of the inverse transform to the input function for several anticipated waveforms gave us very respectable results. A system demonstration is under construction.

The time response of scintillator materials historically limited our ability to measure some plasma conditions. In the past we demonstrated that we can decrease a scintillator pulse width by introducing chemicals into the scintillator that provide a nonradiative decay path to the scintillator molecules; that is, some of the scintillator excitation energy is transferred to a nonradiating species. This process is extremely inefficient because the additive chemicals tend to quench the efficiency at every energy-transfer step. In 1983, we demonstrated an exciting new concept, in collaboration with Hebrew University and EG&G, Inc. We succeeded in introducing bromine into selected positions in p-terphenyl (PT) molecules. The bromine causes singlet-triplet manifold transitions and effectively quenches the PT scintillation; it does not quench the other energy-transfer steps. As the PT scintillation provides the rate limit in PT-based scintillators, this intramolecular bromine quench effectively removes this limit. This quenching technique provided a new class of ultrafast, high-efficiency scintillators with many applications.

X-Ray Physics and Spectroscopy

In recent years x-ray measurements have played a fundamental role in the interpretation of physical conditions in nuclear explosive devices, in ICF targets, and in many high-density, hot-plasma applications. Some such applications can be interpreted in terms of thermal equilibrium emissions that require relatively simple broadband x-ray diagnostic instruments. However, there is a growing need in all these applications, and especially in pursuit of x-ray laser concepts, to diagnose nonequilibrium plasmas where high-resolution x-ray spectroscopy becomes essential. We also find, as measurement techniques are pushed to wider applications and greater refinement, that some basic x-ray physics parameters are inadequately known. Examples are fluorescence yields, atomic form factors, photoemission and scintillation parameters, film sensitivities, and many types of interaction cross sections between x rays and matter in different states.

We are developing three beam lines at the National Synchrotron Light Source (NSLS) to enhance the plasma diagnostics effort in Group P-14, to measure basic plasma and atomic physics phenomena, and to increase the Laboratory's x-ray measurement capability. Two of the beam lines will be on the 750-MeV storage ring and will deliver photons in the soft x-ray regime; the third will be on the 2.5-GeV x-ray storage ring and will cover the medium-energy x-ray range. The total system of beam lines will cover the energy range from 25 eV to 25 keV.

To implement these beam lines we obtained one port on each of the electron storage rings at NSLS through the competitive proposal system. In addition to the beam lines, we are building a new pulsed x-ray source capability at Los Alamos and upgrading our present x-ray source characterization facility, for which we have FY84 funding.

In support of the plasma diagnostics effort, we measured the properties of a series of metal multilayer dispersion elements. These elements are thin film-layered structures made of alternating layers of heavy and light materials (for example, tungsten/carbon) that diffract x rays much like natural crystals but can be made with specific properties (for example, large-layer spacing) to optimize specific measurements. In addition we studied a series of transition metal/carbon multilayers to determine optimum conditions and materials for high normal incidence reflectivities. The optical constants of the materials and the smoothness of the interface between the layers affect the reflectivity. Because the reflectivity is reduced exponentially by the interfacial roughness, this parameter is very important. We found that an iron/carbon system performed well for large-layer thicknesses when surface roughness is not critical but that a rhenium-tungsten/carbon system had a higher reflectivity for thin-layer systems.

A significant fraction of the needs for expanded x-ray capability falls in the area of crystal spectroscopy with both plane and curved geometries. This year we developed two elliptically curved systems similar to that shown in Fig. 21. A source of x rays at one focus of an ellipse emits x rays that

Fig. 21. Bent crystal elliptical spectrograph geometry.

undergo Bragg diffraction by a crystal on the elliptical surface and converge to the second focus of the ellipse, after which they diverge according to energy (or wavelength) to dispersed points in a detection surface located at a distance r_d . Figure 21 shows a spectral resolution element of size $H \times d$ falling upon a fiber-optics bundle. A scintillator interposed just before the fiber-optics bundle converts the x-rays into blue light, which travels along the fibers to some multichannel detector such as film, a streak camera, or a CCD. One system we developed employs fiber optics coupling to a streak camera. The second system is a discrete multichannel version in which a narrow scintillator intercepts the x-ray beam and emits blue light directly into a photodiode detector. A separate scintillator/photodiode combination is used for each channel of information. In addition to specifying the design parameters and calculating the x-ray efficiencies of these systems, we developed laboratory facilities for processing test crystals and calibrating the final elliptical spectrograph assemblies.

For the Inertial Fusion program, we acquired a new x-ray streak camera and modified existing x-ray streak cameras. We extended the detection range into the subkilovolt x-ray region for diagnosing thermal sources. We also developed a capability to measure the spatial resolution characteristics of these instruments, using a short-pulse, high-energy, glass laser to generate a fast x-ray pulse. Recent measurements have demonstrated x-ray streak cameras with resolution approaching 20 lp/mm in the sweep mode.

Neutron Measurements: Group P-15 N.S.P. King, Group Leader

The conception, definition, execution, and interpretation of weapons physics experiments at the NTS form the major part of the work of Group P-15. Areas emphasized by Group P-15 include precision hydrodynamic yield determinations; absolute nuclear radiation flux and energy spectral measurements; imaging in the nanosecond domain with high-resolution imaging Techniques and active downhole instrumentation, such as streak and video cameras; image data processing; and fiber-optic data transmission and temperature diagnostics.

To enhance and maintain a state-of-the-art capability to develop new experiments and investigate complex nuclear, atomic, and plasma physics phenomena, group members frequently carry out basic and applied physics measurements in a number of other laboratories as well. Extensive interaction with

electro-optics and electronics corporations through development contracts also provides group members with the experience necessary to address the constantly changing requirements in the weapons physics community.

The following material describes some of the technology projects rather than experiments currently being investigated in Group P-15.

Neutron Measurements

Indium phosphide (InP) devices have been under development at Los Alamos National Laboratory for several years. Although the major interest was in their use as photodetectors and fast photoconductors for switching applications, they can serve also as fast detectors for charged particles.

In collaboration with Group E-11, Group P-15 developed InP devices as proton detectors with high bandwidth. These detectors were fielded in NTS diagnostic packages for neutron flux measurements utilizing proton-recoil telescopes. The time response of a typical NTS detector to an electron pulse of ~ 50 ps FWHM is shown in Fig. 22.

Initial trials of InP detectors at NTS showed promise and indicated some problems requiring further study. After this experiment, InP detectors were fielded in geometries permitting a direct comparison with the standard Faraday cup and silicon detectors previously used in these applications. The time response proved to be excellent, and the absolute sensitivity as determined by comparison to the Faraday cups was within 30% of predictions. On the basis of these data, we modified the contact configurations to permit more accurate calculations of the absolute InP sensitivity. Subsequent fielding of the detectors after these modifications resulted in a time response ≤ 200 ps and a sensitivity that can be predicted to within 5%.

At present, we are developing an array of InP detectors for use in the focal plane of a high-resolution proton spectrometer. The InP detector now can be used routinely with confidence wherever a fast, sensitive charged-particle current detector is needed.

A neutron spectrometer for 8- to 20-MeV neutrons is being calibrated at the Los Alamos National Laboratory ion beam facility. The protons scattered by neutrons from a CH_2 foil are momentum analyzed in a quadrupole-dipole permanent magnet system. Some different proton spatial distributions are injected, with the Van de Graaff accelerator, into the spectrometer without the CH_2 foil in place. A slow phosphor (Rarex) scintillates to form an image of the spectrometer-analyzed protons in the focal plane. We record this image by computer for varying incident proton energies using our NTS vidicon systems. Preliminary results indicate that an energy dispersion of ~ 100 -keV corresponds to a 4-mm by 4-cm image near 14 MeV. This is somewhat better than predicted. Work is continuing to prepare this spectrometer for an NTS experiment in 6 months.

Fig. 22. Time response of InP detectors developed for use at NTS. The electron pulse used in this test has a 50-ps FWHM.

Imaging Experiments

Micropinhole Development. A factor of 5 improvement in the resolution of Pinex 14-MeV neutron imaging was achieved with a new uniform taper pinhole design that was optimized for a specific NTS field test geometry. The key to this advance was the design of a small pinhole with minimum leakage of 14-MeV neutrons through the body of the pinhole. A straightforward reduction of the diameter of a typical Pinex pinhole, which has a diameter of ~ 0.35 mm, a center bore length of 2.5 cm, and a pinhole taper mode with stair-step rings, gave too much leakage or too large an "effective" pinhole diameter. Figure 23 shows a schematic of this new design compared with the conventional stair-step design; a uniform taper and a thicker center section were incorporated with the reduced diameter of the center section.

Final pinhole design parameters are optimized for the balance of experimental factors comprising resolution, magnification, flux at the detector, and field of view. In a field experiment with the 50- μ m pinhole, we achieved an overall resolution (including contributions from pinhole, imaging fluor, and TV recording systems) of better than 150 μ m.

Fabrication of the microimaging pinholes and the associated assemblies required a combination of precise metal-working technologies including physical vapor deposition, electroplating, and electrical discharge marking (EDM). A team from the Los Alamos Mechanical Fabrication Division and the Materials Technology Division developed the combination of required techniques and fabricated the pinhole assemblies used to test this new pinhole design.

Optical Shutters. Group P-15 needs an optical shutter of ≤ 1 -ns duration, with dynamic resolution of better than 10 lp/mm over 25 mm, and with a shutter ratio in excess of $10^6:1$.

We achieved the first two of these requirements in a recently developed Silicon-Intensified-Vidicon-Tube (SIT) capable of ~ 12 lp/mm over 25 mm with a shutter time of ~ 300 ps. The shutter ratio is currently only $\sim 10^4:1$ because of incomplete poisoning of the photocathode material deposited on the gating grid. This problem is being solved in a joint project of Group P-15 with GE and EG&G, which is developing a photocathode transfer technique for these tubes.

Fig. 23. Comparison of conventional stair-step pinhole design with the new high-resolution tapered design.

Microchannel-plate (MCP) image intensifiers now available from industry permit $\Delta t \geq 1.5$ ns and resolution ≤ 4 lp/mm. Development projects currently under way are modifying the conductive undercoating on the photocathode and the physical location of the tube components to minimize capacitance between the photocathode and the MCP. We also are evaluating new image intensifiers from four different companies.

Charge Coupled Devices. Solid-state imaging devices offer potentially greater dynamic range and better resolution than our current vidicon systems. In collaboration with Lawrence Berkeley Laboratory, we developed a high-speed readout camera based on a Fairchild CCD222 chip with 488×390 pixel elements. Normal readout frequencies of ~ 8 MHz result in dynamic ranges in excess of 500:1 with uncooled chips. At these frequencies a full frame reads out in ~ 16 ms, which is too long for NTS applications. Our system demonstrates that these frequencies can be increased to 60 MHz, and we will still have a useful picture. However, the requirement for dynamic range of 200:1 or more necessitates slower rates near 30 MHz or frame times of ~ 4.5 ms.

We hope to base a field camera on this work soon. A possible improvement is to utilize a new development chip (CCD231), which does not have the bandwidth limitations of the CCD222. This new chip is unavailable commercially; however, using our prototype camera, we are participating in chip evaluation with Fairchild.

Streak Camera Development. The continually increasing demand for simultaneous temporal and spatial data in many NTS experiments formed the basis for a development program in streak cameras. Examples of such applications are focal plane readout for x-ray, γ -ray, and neutron spectrometers. Time-dependent variations of light from fast scintillators in their focal planes are relayed to streak cameras via large (200-element) fiber-optic arrays.

The streak camera development involves replacing the old RCA streak tubes and their inherent limited capabilities with new tubes being developed by numerous contracts with industry. We currently use SIT-FPS vidicon cameras but are developing a readout system based on solid-state CCD cameras. Various active video readout systems are also being improved.

Data Transmission Links

Group P-15 has an in-house capability for building fiber-optic analog data transmitters. We evaluate numerous laser diode chips for this application and routinely transmit data with bandwidths from 50 MHz to 400 MHz over ~ 1 km of fiber. In some cases transmitters with limited dynamic range but bandwidths of ≥ 900 MHz provided excellent data in NTS environments. The highest-bandwidth transmitters require a considerable effort in coupling the laser diodes to fibers. Increased coupling efficiency can lead to a degradation in bandwidth due to increased modal contributions. Our objective in this program is to provide a means for obtaining high-bandwidth data in our recording trailers with good downhole sensitivity for weak signals until a viable commercial source for transmitters can be found.

An effort is currently under way to use 40-m-long coherent fiber-optic bundles to relay high-resolution time-dependent images to a series of optically shuttered vidicon camera systems on an upcoming NTS event. The initial tests of a system mockup gave very favorable results.

Basic Research

The group performs basic research at LAMPF, the WNR facility, Livermore, and the P-15 laboratories. Recent experiments included 800-MeV (p,n) reactions on various targets that reveal low-lying nuclear excited states, residual Pauli-blocked quasi-free scattering, and quasi-free pion production. The highest energy resolution ever achieved in the (p,n) reaction above 500 MeV is partially due to our experience in transmitting precision timing signals over fiber-optic data links. Pion scattering experiments are continuing at LAMPF to determine pionic excitation of giant resonance through charge

exchange and inelastic scattering. We demonstrated for the first time relative neutron and proton contributions to such excitations.

Channeling radiation experiments are being carried out in collaboration with LLNL; theoretical modeling of line widths, at Los Alamos National Laboratory.

Groups P-15 and CHM-6 collaborate in experiments of liquid excimer physics with potential laser applications.

Data Analysis

Group P-15 maintains a flexible computing capability within the group to support both experimental and theoretical efforts. Heavy use is made of the Laboratory's Central Computing Facility (CCF), primarily the four CRAY-1 computers in the secure partition. Links to these worker machines as well as access to the extensive data storage and output capabilities of the CCF are available to individuals of the group with graphics terminals connected to the Laboratory's Integrated Computer Network (ICN). In addition, several in-house minicomputer systems are supported. A stand-alone, unclassified PDP-11/34 minicomputer operating under RSX-11M is maintained for support of the CORRTEx effort. A secure, classified VAX-11/750 with the VMS operating system is connected to the Laboratory's secure XNET-distributed processor network. This distributed processor (DP), known as P15VAX, provides substantial local computing capability when combined with high-speed links to the ICN. P15VAX is also the back-up facility for the Laboratory's new common event data base system (COEDS). Smaller stand-alone PDP-11/23-based systems are used in applications such as Tektronix SP5 waveform analysis, CAMAC data acquisition, and software development for NTS.

A large part of the computational effort is the modeling of nuclear device outputs to aid in diagnostic experiment design and calibration. Calculations of proposed device designs are made available to Group P-15 by the weapon design groups in X-Division. Computer codes and other software tools, developed in Group P-15 and elsewhere in the Laboratory, are applied to this basic design data to provide the needed predictions. Extensive use is made of Monte Carlo neutron and gamma-ray transport codes to predict signals of interest to a particular experiment designer. Radiation transport and hydrodynamic codes are maintained within the group for shock propagation calculations to assist in measurements of total yield and energy flow in pipes. Calculations of a data-reduction type consume a substantial part of the group's analysis effort. Commercially purchased software is available for applications such as data base management, scheduling and resource management, word processing, and electronic mail.

FUSION PHYSICS: GROUPS P-4, P-5, P-7, P-11, and P-16

Reed Jensen, Associate Division Leader

The fusion physics groups are responsible for the experimental program to explore laser-driven fusion: Group P-4, target experiments and diagnostics; Groups P-5, P-7, P-11, and P-16, laser development, construction, and operation.

During 1983 we continued to explore plasma physics and target experiments designed to elucidate the path to better performance of CO₂ lasers in producing target compression while minimizing unwanted side effects of infrared lasers. We also began preparations for experiments at shorter wavelengths, anticipating the availability of ultraviolet lasers for fusion research.

The Antares system was completed in 1983 and made available for experimental work. In a series of shots, we were able to extract over 20,000 J from the two amplifiers in the system. Although work is still under way to improve the beam alignment and overall workability of the system as well as to increase the total energy output, we now consider the Antares construction complete. Work on a shot schedule is about to begin.

A large-aperture (1-m by 1-m) KrF laser amplifier, the LAM, was constructed and is in its start-up phase. This amplifier is the final-stage amplifier for Aurora, a fusion prototype system that is the forerunner of a demonstration system for KrF laser fusion technology. With LAM and Aurora systems, we can demonstrate the technical and economic feasibility of multiplexed KrF laser systems for ICF applications. The large-aperture module will be capable of delivering 100 kJ of electrical energy into a 1-m³ gas sample. In its start-up phase the module will be operated as an unstable resonator, but eventually it will be as a prototype amplifier for a train of angularly multiplexed short pulses.

Fusion Experiments and Diagnostics: Group P-14

P. D. Goldstone, Group Leader

Introduction

The Fusion Experiments Group is responsible for carrying out the experimental research in the Inertial Confinement Fusion program. Group members developed and fielded various plasma physics and target interaction experiments to evaluate the eventual feasibility of CO₂ lasers ($\lambda = 10 \mu\text{m}$) as fusion drivers using Helios and just began to utilize Antares, currently the world's most powerful laser system. We also took advantage of the unique capabilities of the Laboratory's CO₂ lasers to study the physics of microwave production by high-energy electrons and possible laser-driven collective particle acceleration concepts. We have studied thermal transport of energy in directly illuminated targets at shorter wavelengths (1 μm) to resolve major issues in short-wavelength target design.

ICF Experiments at 10 μm

The Evaluation of CO₂ Target Concepts. We investigated several target concepts for use with CO₂ lasers exploiting the different major energy flow channels in the CO₂-target interaction [suprathermal electrons ($\sim 100 \text{ keV}$), thermal radiation and hydrodynamics, and suprathermal ions] as routes toward driving hydrodynamic implosions of fusion targets. A major emphasis in this research was the determination of energy balance and flow in these targets and the scaling of the energy balance to reactor energies and reactor target levels. Absorption of laser light and fast-ion production represent major elements in the conversion process from photon energy to particle energy. For spherical targets, the absorption A was found to vary from $\sim 30\%$ to $\sim 60\%$ as intensity is increased from 10^{14} to 10^{16} W/cm^2 . This represents the conversion efficiency of the light to high energy electrons in the plasma corona. The energy of the energetic electrons is further partitioned into fast ions (collisionless loss of electron energy to ion acceleration) and energy deposited in the target. The energetic electrons try to leave the target and in so doing impart some of their energy to ions in the coronal sheath. The fraction of absorbed energy in

fast ions, F , also varies from $\sim 30\%$ to greater than 60% with intensity on spherical targets because of the high electron temperatures produced as intensity is increased (up to ~ 300 keV at 10^{16} W/cm 2). The deposited energy, given by

$$E_D = E_0 A(1 - F) ,$$

is at most $\sim 20\%$ of incident energy and essentially independent of intensity on target. Other measures of deposited energy in thin ($1\text{-}\mu\text{m}$) spherical targets (derived from bremsstrahlung or thermal radiation) typically indicate less useful energy, but Fig. 24 shows that our energy budget on these targets is consistent to $<10\%$ of incident energy. Targets thick to hot electrons typically have about 15 to 20% useful deposited energy as determined from all techniques.

For directly driven spherical targets, another inefficiency of a factor of ~ 2 relative to an "ideal" driver is due to the energy deposition profile of hot electrons deep in the ablator (see the following section for more details). Thus, the overall effective coupling efficiency for directly driven spherical targets is approximately 10%. All other target concepts we investigated have similar or smaller overall target-coupling efficiencies when we scale them to reactor energy levels based on Helios experiments. These results, if verified with Antares experiments at ~ 30 kJ, would indicate that CO $_2$ lasers are significantly less efficient at driving targets than is desirable for current reactor concepts. The increased energy and larger depth of focus of the Antares beams will allow Antares experiments to investigate possible changes in the scaling of energy balance and hot-electron temperature relevant to the target concepts we have considered.

Suprathermal Electron Transport and Deposition in Spherical Targets with Thick, Low-Z Ablators. Because most of the laser energy incident on CO $_2$ -laser-irradiated targets appears as suprathermal (hot) electrons, the transport and deposition of this electron energy in spherical targets with realistic ablator thicknesses are of basic importance. Of central importance is the question: how much ablator material is required to reduce preheat in the fuel to an acceptable level?

To address this preheat issue, we studied electron transport in spherical targets having a central copper ball covered with various thicknesses of CH plastic (Fig. 25). The copper serves to identify (by the emission of characteristic K $_{\alpha}$ radiation) the penetration of hot-electron energy through the plastic. The main target sequence was composed of 255- μm -diam copper balls with CH thicknesses varying from 50 to 190 μm . Targets with the same outer diameter, but with larger copper spheres in the center, are fiducials for energy deposition and CuK $_{\alpha}$ yield; furthermore, intercomposition of large- and small-ball yields (aided by Monte Carlo calculations) also helps us determine the directionality of the incident hot electrons, which are nearly isotropic.

Fig. 24. Energy flow in thin gold shells irradiated at $\sim 10^{15}$ W/cm 2 . Various means of estimating the useful energy deposited in the shell agree to within $\sim 10\%$ of the total energy.

Fig. 25. Targets for a spherical electron transport experiment. The copper ball produces both characteristic K_α radiation and bremsstrahlung from hot-electron bombardment. Different sizes of copper balls can be used to determine the isotropy of hot-electron flow.

Two focal conditions were employed. The shorter defocus gave a mean intensity of $\sim 1 \times 10^{15} \text{ W/cm}^2$ over a spot size of $\sim 270\text{-}\mu\text{m}$ diam and an experimental electron “temperature” (from the slope of hard bremsstrahlung emission) of $T_H = 115 \text{ keV}$. The longer defocus gave corresponding values of $\sim 2 \times 10^{14} \text{ W/cm}^2$, $\sim 750 \mu\text{m}$, and 57 keV . The shorter defocus gave fairly uniform irradiation, whereas the longer defocus produced the best uniformity yet attained in our CO_2 experiments.

Many different diagnostic instruments were employed, and all gave useful data. However, the data bearing most directly on issues of energy deposition and transport came from the hard-x-ray spectrometer and the two independent crystal spectrometers employed to measure absolute CuK_α yields.

The CuK_α data of photon yields versus CH thickness for the higher intensity shots are shown in Fig. 26. Superimposed are three LASNEX simulation results for $T_{He} = 50, 100$, and 200 keV . By interpolation, we find the best LASNEX fit to occur at about 80 keV , for an assumed 3-D maxwellian electron distribution. (A 1-D Maxwellian gives about 120 keV .) By comparison, the hard-bremsstrahlung slope gives $T_{HX} = 115 \text{ keV}$, which is remarkable agreement for such different physical measurements of electron deposition. Measurements of bremsstrahlung production in the copper ball as a function of ablator thickness are also consistent with the K_α measurements of electron penetration.

The apparent “preheat levels” through $190 \mu\text{m}$ CH (defined here as the observed CuK_α photon yield from a $255\text{-}\mu\text{m}$ -diam copper central ball surrounded by $190 \mu\text{m}$ CH, divided by photon yield from a $630\text{-}\mu\text{m}$ -diam copper ball coated with only $6 \mu\text{m}$ CH) were 3 for the higher intensity and $\sim 0.5\%$ for the lower intensity, although the target energy balance is roughly the same in the two cases. Both of these preheat levels are a factor of 2 lower than we anticipated in the target design study that used simple models of electron transport.

These experimental preheat levels are highly dependent on the particular solid angle subtended by the copper sphere from the CH surface, as well as on the ablator thickness. Nevertheless, a significant ablator thickness and/or a large ratio of target diameter to ball diameter can hold preheat down to manageable levels. Thick ablators considerably reduce the efficiency of converting the 20% of incident energy deposited in the target into useful hydrodynamic motion.

Fig. 26. CuK α signal versus carbon hydride ablator thickness. The data are best modeled with a characteristic temperature of ~ 80 keV.

Ion Pinhole Camera Measurements at Helios. The suprathermal ions generated in the CO $_2$ laser-target interaction are a large energy channel that may be exploited to drive targets, provided this energy can be transported effectively. To increase our understanding of the fast-ion plume, which is generated when CO $_2$ laser light impinges on a surface, fast-ion pinhole cameras were installed on Helios to obtain a direct image of the ions coming from target surfaces. The cameras were standard x-ray pinhole cameras modified to use a track-etch detector (CR-39) to image the ions. The track-etch material was covered with a mylar filter to select ions having energies greater than about 300 keV (1 amu).

Figure 27 is an ion pinhole photograph of a spherical target. The dark areas are the locations of the laser beams where there is intense ion emission normal to the surface of the target (away from the camera aperture) and less emission towards the camera. This picture is consistent with other data and simulations that show ion plumes normal to irradiated surfaces under the beam spots. We believe the larger "glow" area, which shows ions coming toward the camera from beyond the target surface, is due to an ion-ion instability that scatters the highly directed ions in the expanding plasma and results in velocities at large angles from the plume direction.

Subsequent photos taken on plane targets corroborate the model of the ion-streaming instability as a primary factor determining the ion angular distribution.

Antares Diagnostics and Initial Target Shots. The initial set of primary target diagnostics developed for Antares experiments included pinhole cameras for x-ray imaging, a soft x-ray spectrometer for measurement of thermal x rays in radiation-driven targets, a hard x-ray spectrometer for determination of hot-electron temperatures and the energy deposited in the target by hot electrons, and an array of 36 ion calorimeters for determination of absorbed energy, energy lost to fast ions, and the fast-ion spectrum. In addition, to aid in determining the quality of laser illumination on target, we fielded two optical "prelase" detectors, which detect visible plasma emission from the target as a sensitive indicator of prepulse-produced target plasma, and a fast-ion time-of-flight system (the ion velocity spectrum is significantly perturbed by laser light on target prior to the main laser pulse).

From December 22 to December 30, 1983, we obtained nine target shots on 8-mm and 3-mm targets to test these diagnostics and verify the absence of prepulse light on target. All of our diagnostics provided useful signals with good signal-to-noise ratios. We obtained no indication that prepulse or prelase is a problem for present or future target experiments. To prepare for the target experiments that

Fig. 27. Ion pinhole photograph of a spherical target. Dark spots appear where the ions are strongly collimated normal to the target surface, away from the camera aperture.

begin in early 1984, we are addressing several minor data acquisition issues we uncovered in this shakedown series. Simultaneously, we are adding to our diagnostic competence to provide a more comprehensive experimental capability for these experiments.

Plasma Physics Experiments With CO₂ Lasers

High-Frequency Microwaves Produced by High-Intensity CO₂ Laser Radiation. Intense microwaves in the 25- to 36-GHz range have been observed from plane aluminum targets irradiated by CO₂ laser light in the intensity range from 10^{14} to 10^{16} W/cm². Microwaves have long been noticed as a source of noise in Helios instrumentation, and our study was undertaken to improve our understanding of the CO₂ laser-plasma interaction. Although we do not yet understand the details of the generation mechanism of the microwaves, we have begun to parameterize the microwave emission experimentally.

The experimental arrangement consisted of a rectangular wave-guide system placed to view the target and fed through the Helios target chamber wall. The signals were detected by a diode at the end of the waveguide and recorded on an oscilloscope inside a shielded screen room. With the assumption that the microwaves were produced only during the laser pulse (1 ns) and with the known dispersive properties of the wave guide, a frequency spectrum of the signal was obtainable.

The data show that the microwave signals are strongly correlated with the yield of hard bremsstrahlung x-rays Y_{XR} [Fig. 28(a)]. The hard x-ray production is a function of both laser energy and hot-electron temperature via the thick-target bremsstrahlung relationship $Y_{XR} \sim E_{ABS} T_H$ with the scaling law for hot-electron temperature with intensity $T_H \sim I^{0.4}$ and $E_{ABS} = E_0 A$. We can rewrite this as $Y_{XR} \sim E_0^{1.4} A$ for fixed laser spot size. Because the absorption fraction A also increases rapidly with intensity, for

a fixed focal spot, the hard x-ray yield and the microwave power increase rapidly with increasing laser energy.

Figure 28(b) shows the microwave signal as a function of the angle of the target relative to the detection axis. There is apparently no strong angular dependence.

The power output of the surface-generated microwaves was found to be as high as 60 MW at the target, which represents an efficiency of about 10^{-4} and indicates a potentially useful unique short pulse of microwaves in this frequency range.

Helios Laser Beat Accelerator Experiment. Some of the interaction physics of laser beat acceleration was investigated in a preliminary experiment at Helios. The "laser beatwave accelerator" accelerates charged particles in the traveling electric field of an electron plasma wave excited in an underdense plasma. The plasma wave is produced by the beating of two laser beams with different frequencies, so that the plasma frequency ω_p is the difference between the two laser frequencies. In effect the beat accelerator concept is an rf linac in which the plasma replaces the rf accelerator structure. Plasma simulations have shown that electrons are also accelerated to high energies by the interaction of a single intense laser beam with an underdense plasma; this preliminary experiment was designed to look for those electrons.

Fig. 28. Microwave production from planar targets (a) as a function of hard x-ray production and (b) as a function of target angle.

Figure 29 shows the geometry of the Helios experiment. The underdense plasma was produced on a plastic target with one of the laser beams; a second laser beam was focused on the plasma at varying distances from the target and delayed by 4 ns from the first beam. In this way, we selected electron densities in the interaction volume varying from above critical to far below critical density for CO_2 ($10^{19} \text{ e}^-/\text{cm}^3$). Because the plasma frequency varies with density, the matching conditions varied between the input laser beam and the plasma waves. A pair of thresholded Cerenkov counters ($E > 15 \text{ MeV}$) detected electrons, and the Helios high-energy photon spectrometer detected bremsstrahlung x rays produced by electrons in a gold backing on the plastic targets. Backscatter diagnostics were also available on the interaction laser beam line so that $2\omega_0$ and $3/2 \omega_0$ light could be measured. Production of $2\omega_0$ and $3/2 \omega_0$ light can be traced to the presence of the critical and quarter-critical density surfaces in the interaction volume.

Preliminary analysis of the data showed that at densities between quarter-critical and critical, no fast electrons were detected by either the hard x-ray system or by the Cerenkov counters at a laser intensity of about 10^{16} W/cm^2 . A major difference between the experiment and the simulations, which show a considerable, accelerated electron flux, is that the laser risetime is much longer than the assumed risetime in the calculations. The simulations also only show hot-electron production in the very early parts of the pulse. Simulations are being performed to identify further experiments, possibly using more than one frequency of laser light, for a higher probability of producing detectable high-energy electrons.

Short-Wavelength Experiments

Detailed Measurements and Analysis of Near-Classical Thermal Transport in $1\text{-}\mu\text{m}$ -Irradiated Plasmas. The transport of energy from the absorption region to the ablation region of laser-irradiated targets has remained a topic of active investigation and controversy for nearly 10 years. Early work largely involving flat targets indicated a severe limitation of the heat flux relative to classical predictions as measured by the amount of mass ablated from the target surface by the laser-generated heat front. More recent work involving spherical targets has yielded transport results closer to classical. In the present experiment we studied transport and plasma evolution in spherical targets at $1 \mu\text{m}$ using the glass laser at the Rutherford Appleton Laboratory, UK. A wide range of diagnostics provided a more

Fig. 29. Geometry of the laser beatwave accelerator experiment (see text).

comprehensive picture of the plasma conditions than did previous work. For example, the combination of time-resolved x-ray line spectroscopy to detect propagation of the heat front and interferometric probing to determine the ablated plasma profile places important constraints on the theoretical modeling.

The basic target configuration used in most of the work is shown in Fig. 30. The solid glass ball prevented any implosion of the target (and subsequent inward movement of the critical surface) during the shot. In most cases, the targets were uniformly illuminated with the six-beam laser facility at the Rutherford Appleton Laboratory. Focusing conditions were adjusted to provide uniform plasma expansion as determined by interferometry while minimizing refraction of laser light in the target corona. Incident irradiance levels ranged from 3 to 8×10^{14} W/cm². The laser pulse had an approximately Gaussian temporal profile with a 0.8-ns half-width.

The primary diagnostic of thermal transport was time-resolved x-ray line spectroscopy in which a streak camera is the detector in a crystal spectrograph. X-ray line emission was observed primarily from silicon (in the central glass sphere) and the thin aluminum layer. A few lines were also observed from sodium, calcium, and magnesium impurities in the glass. By observing line emission from these different target layers, we determine the transit time of the heat front through the target. These data can be used to determine the rate of mass ablation during the laser pulse. Relative timing between different elements in the same target layer enables a bound on the steepness of the temperature profile in the heat front.

A 40-ps 3ω interferometric probe ($0.35 \mu\text{m}$) was used to measure the density profile in the expanding plasma ($n > n_c$). This information is helpful in constructing theoretical models of the experiment. Ion calorimetry was used to measure absorbed energy (for uniform illumination, the absorbed fraction measured in these experiments was about 27%).

Faraday cup measurements of the ion blow-off gave us the ion expansion velocity from which we made a separate measurement of mass ablation. Faraday rotation was used to detect laser-produced magnetic fields when nonuniform illumination was employed. Pinhole x-ray imaging enabled a check on illumination and energy deposition information. Time-integrated crystal x-ray spectroscopy and an x-ray diode array measurement of the continuum complemented the streaked line spectroscopy and completed the picture of x-ray emission from these targets.

An example of a time-resolved line spectrum is shown in Fig. 31. Clear time delays can be seen between the time fiducial corresponding to the incident laser pulse on target and the onset of aluminum emission and between the aluminum and silicon emission. Theory and experiment show a very rapid rise (<100 ps) for the onset of silicon and aluminum emission. The delays are thus well-defined

Fig. 30. Target configuration for the 1- μm thermal transport experiment at Rutherford Appleton Laboratory.

Fig. 31. Time-resolved spectrum showing some delays between the incident laser pulse, emission from the aluminum layer, and emission from the glass substrate.

quantities. Average mass ablation rates can be obtained by taking these intervals as the time needed to ablate either the outer plastic layer or the aluminum inner plastic layers. Mass ablation rates determined in this way appear to be lower than those obtained at the University of Rochester using time-integrated x-ray spectroscopy as the diagnostic of the amount of mass required to prevent the heat front from burning through to the emitter layer.

X-ray emission was also observed from calcium in the glass. Very little difference was observed between delays measured for silicon and calcium. This qualitatively indicated a relatively steep heat front, since these elements, of very different atomic numbers, produce x-ray line emission at different temperatures. This result significantly differs from the Rochester results, which indicate a significantly greater mass is required to prevent the penetration of the heat front at temperatures sufficient to produce aluminum line emission than at temperatures required to produce titanium line emission.

The present experiments were modeled with the Lagrangian hydrodynamic code LASNEX. We found that the onsets of emission from the aluminum and silicon layers could be modeled best with effectively classical heat flow. The LASNEX modeling also reproduces the observed absorption of $\sim 27\%$. The relatively small difference between silicon and calcium emission is also consistent with the relatively steep temperature profile predicted by LASNEX. In Fig. 32, we show a direct comparison between the LASNEX transport calculation and experiment.

We are also pursuing more detailed modeling of the heat-front profile by postprocessing the LASNEX runs with a collisional radiative spectral code. When this modeling is complete, we will use line ratios and absolute intensities to infer detailed characteristics of the heat-front spatial profile.

In conclusion, the present experiments are consistent with a picture of near-classical thermal transport. Further theoretical work should yield even more details of the heat penetration.

Optical Science: Group P-5
A. C. Saxman, Group Leader

The Optical Science Group provides expertise in optics, beam alignment and diagnostics, and system integrations to Laboratory divisions in support of major Laboratory projects and experiments.

The technical and programmatic activities and accomplishments of Group P-5 centered on Antares, the Free-Electron Laser (FEL) project, the KrF laser projects, the Special Isotope Separation (SIS)

Fig. 32. A comparison of the experiments (a) with the LASNEX predictions (b) of the time-resolved line emission for a typical shot. The experiment is consistent with effectively classical thermal transport.

projects, and a few special study efforts such as an Expert Lens Design program. The following contributions discuss some significant accomplishments from selected subsystems of the projects.

Antares Beam Alignment

The Antares Beam Alignment System was operational in amplifiers no. 2 and no. 5 for parasitic and energy extraction tests all the way to the target. High-energy shots have been made on targets for initial calibration purposes. We demonstrated the system's intended objectives of aligning the power amplifier components to $\pm 30 \mu\text{m}$, well within the required $\pm 500 \mu\text{m}$, and alignment accuracies on targets were achieved to within $\pm 17 \mu\text{m}$, well within the required $\pm 25 \mu\text{m}$. The system has been very reliable and will be further enhanced with additional automatic alignment software.

Antares Beam Diagnostics and Energy Extraction

The Antares beam diagnostics have been installed through the system for all 24 sectors from two amplifiers. The integrated components include the input calorimeter; input sector calorimeter; 12-sector full-power Kapton-copper foil calorimeters, of which one sector has a five-by-five array detector arrangement capable of measuring the energy distribution over the trapezoid-shaped full-power beam of a single sector; turning chamber calorimeters and high-speed detectors capable of making time-resolved measurements ($>70 \text{ psec}$) of the sampled high-power beams; and target chamber cone calorimeters used

for parasitic stand-off measurements between the target volume and the amplifiers. Both amplifiers were operated in a fully integrated mode up to the 30-kJ energy level. The spatial energy distribution uniformity within one sector is better than 20%. Figure 33 shows a spatial distribution from sector to sector with the input sector energies indicated on the outside circle of the calorimeters, and Fig. 34 shows the detailed energy distribution within a single sector. The full-power calorimeters used in these measurements have a precision of 3%, which exceeds any known commercial unit in the energy range of 50 to 1500 J.

Free-Electron Laser Activities

The initial power and stability measurements of the 10.6- μm FEL system were very successful. The near-concentric stable resonator and alignment that were designed, fabricated, prototyped, and installed easily met all of the requirements with the 1-Hz pulsed rf power system and an untapered wiggler, the output power for a 1.5% output coupling mirror reached 1000 W rms for a 100- μs pulse train of 2000, 30-ps duration micropulses separated 50 ns apart. The output energy distribution agreed very well with predictions. The diffraction losses were less than 2% as predicted, and the cavity gain was very

Fig. 33. Spatial distribution of energy, shot no. 8683, all sectors, Antares.

Fig. 34. Spatial distribution of energy, shot no. 8683, sector 5, Antares.

insensitive to deliberate mirror misalignments. The system is very robust as predicted by earlier propagation analysis, which helps to further the benchmark quality of the Los Alamos diffraction propagation codes.

The initial Visible FEL Simulation experiments have commenced. A 67-m, near-concentric stable resonator with a Fresnel number of one was successfully operated at 488 nm. Two argon-ion tubes were used as the optical gain source in place of the FEL wiggler. The initial beam wavefront and intensity measurements showed that the system runs in the TEM₀₀ mode with a wavefront distortion of less than $\lambda/8$ peak to valley. As predicted, the resonator alignment was easily maintained with simple manual alignment techniques. The diffraction characteristics of the cavity permit large obscurations of the beam to occur before the lasing action stops. The resonator will next be modified to include automatic alignment procedures, and a number of new resonator concepts that can provide for high-power mirror fluences will be evaluated. Integrated system concepts were also generated for these types of cavities to reduce their size and weight for projected high-power systems. In addition, P-5 personnel introduced some unique concepts for the high-power acquisition and pointing subsystems that will be incorporated into the study concepts.

Aurora and Polaris KrF Laser Projects

The Aurora prototype system project is to help define, clarify, prototype, and demonstrate the technology base for a high-energy, single shot, 50- to 100-kJ, 5-ns, KrF target shooter, Polaris, operating at 248 nm. A basic optical point design of the multiple beam (~ 100) multiplex Aurora system was completed. Detailed optical designs, procurements, and further analysis have commenced for optical elements, positioners, initial alignment systems, and basic support structures. One of the primary objectives of the Aurora is to generate cost-benefit models for scale-up cost models for the Polaris project. To this end a detailed project work package structure was generated detailing development, procurement, assembly, and integration costs for all of the optical items. This task will continue throughout the Aurora project, and necessary adjustments and extrapolations to Polaris requirements will be made. The initial Polaris concept design contracts with industrial corporations are being evaluated for technical content and programmatic issues. A Los Alamos design team will be formed to guide and interface outside contractors in this exciting new project.

Special Isotope Separation (SIS) Projects

Group P-5 recently has been supporting the laser-induced isotope separation for the uranium isotopes, SIS III, and the plutonium isotopes, SIS III. The SIS III concepts and prototypes are being evaluated on an operational test station of the SIS II project. Innovative concepts employing clever arrangements of prisms to enhance the separation efficiency by multiple beam passage through the gas species and beam propagation techniques for modifying and controlling the beam's intensity profile in the gas separation region have been developed. The recently developed Los Alamos beam propagation codes have been of immense value in qualifying and giving insight into the beam propagation characteristics of the multiple laser beams passing through the species' separation regions. The propagation codes can now describe the diffraction effects of multiple beams with varying wavelengths, ranging from the ultraviolet to infrared wavelengths, interactions with absorbing dispersive media, oddly shaped apertures, various beam path inhomogeneities, and complex optical components. The overall system performance and simplicity have been greatly enhanced with the use of these codes.

Expert Lens Design System

An "intelligent" computer program capable of designing image-forming optical systems without human guidance and of improving its performance with time is being developed. The design of image-forming optical systems was selected as a specific vehicle for the development of the general approach.

The rationale is that these optical systems can be designed and their performance determined and evaluated with reliable codes that find optima with proper human guidance. The general approach to the development of the intelligent design program is based on the interpolation of one subspace of characteristic prescribed parameters into another subspace of derived characteristics. For example, for an optical system the specified characteristics could be an f-number, field of view, focal plane line-pair resolution, total optical power of the system, and geometrical envelope. What is needed for manufacture and what must be derived, subject to image quality requirement, are the surface radii of curvature of elements, their thicknesses, indices of refractions relative positions of the elements, etc. With mapping from one mathematical subspace into another, better use of the large memory and manipulative speeds of the large main frame computers is possible as compared to the "if-then" production rules that are commonly employed in standard artificial intelligence programs. Examples for a two-element optical system have brought very good results. We believe that the resulting design program will be useful in current optical design procedures and practices and could be extended for other design tasks.

Laser Pulsed Power: Group P-7

G. Allen, Group Leader

The Laser Pulsed-Power Group is responsible for the general areas of high-voltage, pulsed-power system development and laser systems operations. Within this framework we provide project management and technical support to five projects: Antares, KrF prototype system, Heavy-Ion Fusion Injector, Hypervelocity Projectile Accelerator, and SIS III.

Antares

Group support of the Antares laser project has progressed from the project management and technical implementation phase of two major subsystems to integrated testing and overall laser operations.

At the start of this reporting period, we began a series of energy-extraction and amplifier stability tests. Starting with one of the 12-beam sectors and gradually building up power and adding sectors, we achieved a series of uniform 12-sector shots delivering greater than 10,000 J from each amplifier (Fig. 35). In conjunction with these energy extraction tests, efforts were made to measure and improve the amplifier stability level. With lithium flouride paint and carefully cut baffles, stability (freedom from parasitic oscillations) was achieved at a gainlength product (g_0l) of 7.2. Following these tests, we proceeded with simultaneous firing of both power amplifiers delivering all 24 beams to the target chamber.

This test sequence represents approximately 2,000 shots on the 2 electron guns and 400 shots on the two power amplifiers in various configurations. The culmination of these efforts was 8 full-system target shots achieved during the first week of 1983 in which 3-mm and 8-mm gold-plated copper spheres were hit by all 24 beams at a 10-kJ energy level (see Fig. 15).

KrF Prototype System

Group P-7 has the major responsibility of providing the amplifier chain for the KrF prototype system. This amplifier system consists of four progressively larger amplifiers: small aperture module (SAM), preamplifier (PA), intermediate amplifier (IA), and large-aperture module (LAM). These amplifiers range in energy output from a few joules to several kilojoules of one-quarter micrometer light. During this reporting period, we defined the parameters for the SAM, placed orders and received virtually all the hardware for both the PA and IA, and contributed to experimental tests and upgrading of the LAM. Assembly and testing of components for the PA and IA are now well under way. A detailed description of the system is provided in the Group P-16 section.

Fig. 35. Burn pattern of 12 simultaneous beams from one power amplifier (scale reference, diameter = 8 ft).

Heavy-Ion Fusion Injector Project

In December 1981, Los Alamos National Laboratory, in its capacity as lead laboratory for heavy-ion fusion (HIF), submitted to DOE a proposed "Plan for the Development of Heavy-Ion Accelerators for Fusion Power, 1984-1989" (LA-UR-81-3730). In May 1983, a supplement (LA-UR-83-1717) to the 1981 plan was published. Together, these two documents describe a 6-year program to develop, design, and build an induction linac that will deliver several kilojoules of Na^+ ions to a slab target. Calculations indicate that the target should be heated to a temperature of approximately 50 eV. This program is referred to as the High-Temperature Experiment (HTE). Lawrence Berkeley Laboratory (LBL) is developing the induction linac. The Physics Division at Los Alamos is responsible for the injector.

Because the cost of induction linac modules at low particle energy is very high, it is desirable to inject particles of relatively high kinetic energy using a pulsed electrostatic ion gun. We also plan to use multiple beams within a single vacuum envelope in the induction linac, to increase the current-carrying capability. The following injector specifications are the current goals:

- Injector voltage, 2 MV
- Current per beam, 300 mA
- Number of beams, 16
- Beam diameter, 3 cm
- Ion species, Na^+
- Pulse length, 6 μs
- Beam emittance, $0.4 \pi \text{ mm} \cdot \text{mrad}$

The present main-line design consists of an ion gun driven by a Marx generator. The ion source is a sintered button of sodium-filled zeolite heated to $\sim 1300^\circ\text{C}$. The electrically insulating vacuum jacket

must be ceramic because of the high-temperature anode. The Marx generator and the acceleration column will be surrounded with SF₆ at 45 psig to provide electrical insulation, with the whole system inside a pressure vessel.

Progress was reported on the following tasks listed below

Ion Source. We designed and built an experimental apparatus that will be used to determine the Na⁺ emission characteristics of solid ion sources, the characteristics of interest being primarily current density, uniformity, and emittance (a measure of transverse energy). Experiments will begin in January 1984. We also placed a contract with UNM to develop a pulsed plasma ion source.

Ion Optics. We obtained, and are learning to use, two computer codes SNOW and EGUN, for charged particle beam trajectory calculations. We have designed the optics for the source experiment and are beginning the design of optics for the multibeam injector.

Marx Generator. We began design of the Marx support structure, and we placed a contract with Maxwell Labs to design the stage hardware and test it in an SF₆ atmosphere.

Ceramic Column. We placed a contract at Coors to fabricate 28-in. o.d. by 4-in.-long cylinders (the largest available) of 85% purity aluminum oxide. We are awaiting bids from McDonnell-Douglas for a contract to braze the alumina to niobium rings. We then will test the strength of the bond.

Hypervelocity Projectile Accelerator

The distributed railgun program, a joint effort of M, WX, CTR, and P Divisions, is to develop hypervelocity electromagnetic accelerators for national security applications. During this period the project has focused on two tasks: the HYVAX railgun experiment and the design and analysis of a 30-MJ impact apparatus for use with the Phermex facility.

The HYVAX experiment is proceeding as planned, although several months behind schedule. Assembly of the Phase I configuration, a 10-ft section of rail accelerator, was completed. Preliminary tests to verify structural design and diagnostic systems began in December; completion is expected by the end of January. The Phase II railgun (43 ft) will be assembled in February; experiments are scheduled for the March to April period (Fig. 36).

Fig. 36. Hypervelocity acceleration experiment, HYVAX.

SIS III System Engineering

SIS III is a molecular laser isotope separation program requiring high-repetition-rate lasers. Personnel from Group P-7 are responsible for system engineering for SIS III. Over the life of the project, this involves system design, integration, testing, and operations. The initial phase involves primarily system design.

Objectives. The system engineering staff ensures a fully integrated system design by producing system requirements and specifications, conducting design reviews, and completing design review reports. System reliability is addressed by performing analyses of risk, failure, and lifetime. Value engineering is part of this task to ensure that the design provides the best function for the cost expended. Various trade-offs occur during the design phase to obtain the most effective overall design. Criteria are developed to give direction to the design process.

Trade-offs are also performed during system fabrication and testing because of design changes required by technical difficulties that may be encountered.

During the installation and check-out phase, system engineering provides the overall direction to ensure the timely sequential assembly and testing.

During this period a specific objective was to develop the project requirements document and the system specification. A second objective was to conduct preliminary design reviews for the beam transport, disassociative laser, and compressor glove box subsystems. The final objective was to complete a draft of the system specification tree.

Results and Discussions. We developed a system specification using the information from the draft requirements document. This specification defines the test section performance and lists the requirements for other subsystems. A draft specification tree was completed.

After the transport preliminary design review, approval was given to proceed with the baseline prism design for the nozzle illumination. The major problem to resolve is the damage threshold of the anti-reflective coatings, but lack of damage information will not delay the design.

The disassociative laser preliminary design review was held, and the results of the prototype acceptance test were presented. The key feature of the disassociative laser design is the decision to use smaller commercial lasers rather than larger units, which would require considerable in-house development.

Criteria were developed for the process support building, which will be adjacent to the plutonium building. These criteria were given to The Zia Company, which completed the building procurement specification. This support building will house the selective and disassociative laser systems (see Fig. 37).

Group P-7 personnel were pivotal in the design and implementation of the HYVAX experiment. A microcomputer-based data system was developed to collect and analyze 30 channels of information on accelerator performance. Additional responsibilities included installation and testing of the projectile injector, the vacuum system, and their associated controls.

The design and analysis of the proposed 30-MJ impact system has been supported by Group P-7 in pulsed power system design and launcher performance predictions. Substantial work of this nature was also performed to support external agencies including the Air Force and the Army Ballistics Missile Defense Agency.

Instrumentation and Control: Group P-11

M. Thout, Group Leader

Group P-11 provides electronic and software engineering expertise to P-Division to support three projects: the Antares CO₂ Laser, the Aurora KrF Laser, and the SIS III Laser Isotope Separation. We provide project management and technical support for the controls and instrumentation of major project subsystems: pulse power, laser power amplifiers, front and/or end, timing and firing, optical alignment, optical diagnostics, rep-rated lasers, process flow loops, and integrated facility operation.

Fig. 37. Process support building showing selective and disassociative laser arrangement.

Antares CO₂ Laser Project

Major control system activities of Group P-11 were the on-schedule completion of integrated facility control software and the completion of automatic alignment controls and software.

With the present implementation of Antares integrated control, any combination of pulse power systems and laser amplifiers (including a full power shot with both beamlines, front end, and laser diagnostics) can be tested, brought to a fully charged state, and automatically fired with full data acquisition capability. Only a few buttons need be pressed on the computer terminal of the integrated control touch screen. The integrated control scheduler program coordinates operation of the 39

computers and over 1500 data and control channels in the Antares computer network to provide the capability for an integrated shot.

The automatic alignment software provides control for all beam segments on both beamlines from the front end to the target. Automatic target alignment software was also produced.

During the operational phase of the Antares project, we will continue to provide hardware and software maintenance and support for the Antares computer network of 49 computers that provide control, data acquisition, software development, and data analysis for Antares.

Aurora KrF Laser Project

Group P-11 is responsible for the design and implementation of the controls for pulse power, laser power amplifiers, optical alignment, and integrated system control for the Aurora KrF project. Five pulse-power systems and four laser amplifiers will be monitored and controlled by a network of three computers. The tight project schedule required this subsystem to be implemented with technology similar to that used on Antares.

The plan for optical alignment controls is to employ a few interconnected microcomputers. They will enhance and analyze a video signal to determine the position of 96 laser beams and then control 192 motors to properly align the laser beams. This design should provide an order of magnitude improvement in alignment system performance compared with that of the Antares system.

SIS III Laser Isotope Separation Project

On the SIS III project, Group P-11 is responsible for the facility control system, for coordination of laser instrumentation development in CHM Division, and flowloop instrumentation and control implementation in E Division. The SIS III project, in contrast to the laser fusion projects, is being implemented in several phases that include periods of experimental operation during the facility construction. The instrumentation and control system must support the project through several installation and testing phases, as well as during experimental operations, and finally provide an integrated facility control and monitor system that can be operated by plutonium production technicians.

The controls project plan is to provide computer-based data acquisition during the first project phase when operation is primarily experimental. In the second project phase, we will automate the control of the process flow loop and instrument the balance of the 20 lasers in the system. In the third phase, we will provide remote control of the laser systems and integrated facility control from a location in the plutonium facility. To minimize the need to change hardware and software installed in the early project phase, progressive growth of the control system will be supported by growth in a network of computers.

Laser Physics: Group P-16 Richard Haglund

Introduction

The Gas Laser Development Group has a broad charter to work on the design, construction, and characterization of high-power, short-pulse lasers for inertial-confinement fusion (ICF) applications. Group members are currently at work on both CO₂ laser systems (in the Antares project) and on the newer KrF devices (in the Aurora project). Activities include diagnostic development, experimental and theoretical studies in laser kinetics, energy extraction experiments and beam profiling, and pulse propagation studies in high-gain laser amplifier media.

Construction and Performance of the Large-Aperture KrF Module

The KrF Large-Aperture Module (LAM) represents a major new concept in high-power short-pulse lasers for inertial confinement fusion. The basic concept of the LAM was developed by R. O. Hunter of Western Research Corporation under contract to P Division. The salient design features of the LAM relevant to ICF applications include

1. the short wavelength (248 nm) of the KrF laser, which we believe is favorable for target physics,
2. a combination of high electrical efficiency (for converting electron-beam energy into a population inversion) with high energy extraction efficiency, and
3. scalability of the basic module for use in ICF laser amplifier chains.

The fundamental objectives of the LAM activities in Group P-16 are to translate these concepts into a working laser device and to characterize the performance of the machine.

The principal features of the LAM are reviewed only briefly here. The KrF molecule is an excimer ("excited dimer"), which is unbound in the ground state; the spontaneous lifetime of the upper laser level is only a few nanoseconds. In a KrF laser amplifier, then, energy is being radiated away for as long as the laser is pumped by the electron beam—with or without a pulse present for amplification. Because electron-beam pumping is inefficient on nanosecond time scales, long electrical pump pulses are needed to achieve high laser efficiency. On the other hand, target-compression requirements for ICF dictate a pulse only nanoseconds long. The KrF laser designer must thus resolve conflicting demands for short laser pulses and high electrical efficiency.

In the LAM, this conflict is handled by optical multiplexing: the electrical pump pulse is chosen to be relatively long (650 ns), while a train of short pulses (5 ns), encoded in angle and stacked one behind the other in time, is fed sequentially through the amplifier (see Fig. 38). The pulse stacking and encoding are complicated; thus a trade-off is made to optimize amplifier staging and optical complexity. Because the LAM was designed to function as a long-pulse unstable resonator as well as an ICF driver-amplifier, the Aurora configuration is not so optimized, but it will allow testing of major driver issues.

During the early months of 1983, the LAM was assembled in building TSL-85; a photograph of the assembled device is shown in Fig. 39. The population inversion in the laser gas is created by electron bombardment; the electrons are created by an intense high-voltage (650-kV) pulse applied to a field-emission cathode covered with carbon felt. The nominal current density supplied from the cathode is 20 A/cm². The high-voltage, high-current pulse on the cathode is created by discharging two Marx banks through parallel water pulse-forming lines on either side of the LAM. The electron energy is chosen so that, when folded with the electron range distribution function, a uniform energy deposition profile is created in the laser gas. The laser gas is a mixture of roughly 0.004/0.046/0.95 F₂/Kr/Ar, at a pressure of 800 to 1000 torr. With these operating parameters, the LAM should produce 10 to 15 kJ of laser energy.

The first full-scale tests of the LAM were late in June 1983. Lasing action was observed; crude output diagnostics showed an output on the order of 0.5 kJ. Laser-kinetics calculations with realistic pulsed-power profiles confirm that this is about the level of energy we should expect. However, this is far short of the LAM design energy, and further tests confirmed the existence of serious engineering problems in

Fig. 38. Angular multiplexing concept.

Fig. 39. Assembled LAM in building TSL-85.

the pulse-power train. Cooperative efforts between Groups P-16 and P-7 and Western Research Corporation have identified several major trouble points:

1. Lack of simultaneity in the waterline output switches;
2. Emission from the back side of the cathode and gas leaks in the bushings, leading to premature bushing failure even at low voltages;
3. Mechanical design flaws in the switches and bushings; and
4. Failure of the titanium foil window between the cathode vacuum housing and the laser chamber.

Similar problems were seen in other large excimer lasers built in the DoD community, and solutions to the problems are known, in principle.

LAM activities at the close of 1983 were devoted to engineering improvements and pulsed-power diagnostics studies to improve reliability and increase the transmission of electrons from the cathode to the laser gas. Major milestones reached in the LAM project are listed below.

- Operated to 55 kV
- Transferred at 1.3 MV
- Attained 700 kV on diode bushing
- 10-cm A-k gap lets foils survive

- Significant reflected energy
- Drift region screened properly
- Collapse insensitive to B-field
- Energy deposition increased to over 20 kJ per side
- Lasing demonstrated

Pulsed-power calculations using NET2 largely corroborate the conclusions reached experimentally about the sources of inadequate LAM performance. We expect the additions and modifications now in progress to dramatically improve both performance and reliability.

A Prototype KrF Laser Chain for Inertial Fusion: The Aurora Project

With the development of a scalable large-aperture KrF laser module well in hand, the next step in application of the combined-aperture optical-multiplex technology demonstration is now being taken. In the Aurora project, the KrF large-aperture module will become the final stage amplifier for a system producing a multiplexed train of ninety-six 5-ns optical pulses with a total energy of 10 to 15 kJ. The P-16 group effort in this project thus far has focused on developing suitable amplifier staging based on relevant gas kinetics calculations for this system. As Aurora is built, diagnostic studies on the various amplifiers will center on establishing as a benchmark the code calculations.

The preliminary design for Aurora is shown in Fig. 40. The front-end pulse is split up in the encoder to yield ninety-six 5-ns pulses, coded sequentially in time and separated in angle, which are fed through a preamplifier (PA), an intermediate amplifier (IA), and then into the LAM. At present there is no plan to include a final decoder to combine the 96 beams into a single 5-ns pulse, as no target-shooting facility is coupled to the laser technology demonstration.

The laser kinetics of the PA and IA are of particular interest, because neither amplifier will be in the fully saturated regime. The PA, for example, has a geometrical fill factor of less than 0.5, and the amplifier is never driven to saturation. Its performance is therefore dominated by the amplified-spontaneous-emission characteristics of the device. The IA, on the other hand, has a somewhat better geometrical fill factor and does reach saturated operation near the output end. Neither device can be modeled well at this juncture; almost no calculations have been done for unloaded devices like the PA, and the IA is in a difficult intermediate amplification regime where all simple approximations break down.

Fig. 40. Aurora laser, conceptual layout.

Thus, the combination of the PA, IA, and LAM will allow the study of all the kinetic regimes of interest for the design of future excimer lasers for ICF applications. Because existing large excimer facilities do not have this flexibility, the Aurora laser system will be a unique test bed for settling scaling, staging, and pulse-propagation issues. Diagnostic systems to measure details of electron-beam pumping, energy extraction, beam profiles, and amplified spontaneous emission are being built for timely deployment of Aurora.

The Aurora system staging was based on predictions of the kinetics code of A. M. Hunter and T. H. Johnson. This code was developed years ago and is reasonably accurate for the long pulses and low pump rates characteristic of the Aurora amplifiers. However, much new information relating to the complex laser kinetics of the KrF laser has been published recently. Moreover, because the amplifiers of interest are all electron-beam-pumped devices, the Boltzmann transport kinetics can be replaced by electron pumping rates based on empirical (measured) values.

Finally, critical examination of the code revealed that some quenching reactions were not included. This has the effect of overpredicting gain and absorption.

During 1983, we undertook numerous improvements to the kinetics code to render it more amenable to the needs of the Aurora project. The use of electron-beam pumping rates resulted in a 20-fold reduction in memory requirement and a 30-fold decrease in CPU time per calculation; this allows the laser kinetics code to become a building block in an IF amplifier chain-staging code. Formation and quenching rates were added to take into account the most recent experimental data.

Also, the AVCO group recently published gain and absorption data covering the pressures, pump rates, and F_2 concentrations of interest for inertial fusion and the improved Hunter-Johnson code has now been benchmarked against these data [results are shown in Fig. 41(a) and (b)]. The agreement between code calculations and experiments appears to be acceptable for the electron-quenching dominated regime (that is, at low F_2 concentrations and lower pressures). For the regime dominated by heavy particle quenching, that is, reactions such as

the code consistently underpredicts the gain and overpredicts the absorption. This is because heavy particle quenching reduces gain (KrF^*) while increasing the absorbing species Kr_2F^* ; similar processes occur in the argon channels, with argon replacing krypton.

Because the reaction rates for the heavy particle quenching reactions have a strong temperature dependence, tracking the neutral gas temperature and incorporating the temperature dependence of the rates is the next major step in improving code performance.

Fig. 41. Los Alamos National Laboratory kinetics code, reproducing gain and absorption from AVCO 2-atm experiment: (a) gain and (b) absorption.

CO₂ Laser Physics Experiments

Several laser-physics activities relevant to both the Antares laser project in particular and to multiple-pulse propagation in general are using the off-line CO₂ driver-amplifier in the Antares front end. This facility offers a unique capability for studying pulse propagation questions in saturated amplifiers.

In the P-Division semiannual report, July 1—December 31, 1982, preliminary results were presented for multiple-pulse energy extraction in a saturated CO₂ amplifier. Because a single short laser pulse usually extracts only a small fraction of the energy stored in the gain medium, the efficiency of high-power laser systems could be significantly improved by passing a train of several pulses (sufficiently separated in time so that the laser levels are repumped) through the amplifiers. This experiment was designed to investigate the increase in extracted energy obtained when several 1-ns CO₂ pulses are passed through an electron-beam-controlled amplifier.

The amplifier was operated at a pressure of 1200 torr with three different laser mixes: (N₂:CO₂) = (2:1), (1:1), and (1:4). The small-signal gain was monitored on each shot with a cw probe laser ($g_0L = 6.3 \pm 0.5$). Several zirconium/selenium beam splitters were used to generate a sequence of 1-ns pulses, the separations of which were controlled by our changing the distances between the beam splitters. Input and output energies were measured with pyroelectric joulemeters, and the signals also were fed to photon drag detectors so that the relative energy of each individual pulse could be determined. Inputs of $\sim 0.3 \text{ J/cm}^2$ ensured that the amplifier was highly saturated.

Figure 42 shows the outputs (E_{out} and E_{in}) obtained for one- and two-pulse operation (averaged for the three gas mixes). For a single 1-ns pulse, we expect to extract $\sim 0.8 \text{ J/cm}^2$, which is in good agreement with the observed value. However, the *total* energy ($g_0L E_{\text{sat}}$) available in the two inverted vibrational levels is $\sim 1.3 \text{ J/cm}^2$, and two-pulse operation delivered nearly all of this energy. Thus, these data demonstrate that two-pulse operation extracts 56% more energy than does one pulse.

Additional energy is stored in higher CO₂ vibrational levels and in the excited nitrogen. Some of this energy probably can be extracted by additional pulses at later times, when slower relaxation processes have repopulated the upper laser levels.

The recent successful operation of an advanced front-end oscillator by Group P-5 opened the way for additional experiments—now in progress—on two other important pulse-propagation experiments.

One of these is a study of the efficiency of multiple-line energy extraction, in saturated amplifiers. Results obtained some time ago indicated that simultaneous energy extraction on several CO₂ laser lines gives only marginally greater extraction efficiency. We are repeating this experiment with greater accuracy because the new oscillator allows control of the input pulse line content for the saturated amplifier.

The other experiment is devoted to studying the long-pulse (~ 10 -ns) propagation in a saturated amplifier. From our experience with both Helios and Antares, we know that pulses of a few

Fig. 42. Outputs (E_{out} and E_{in}) obtained for one- and two-pulse operation (averaged for three gas mixes).

nanoseconds, whose frequency spectrum encompasses only the highest-gain lines of the 10- μm P-branch, are temporally compressed in traversing a saturated gain medium. This phenomenon arises, in essence, because the high-gain lines tend to extract the stored energy as fast as possible—which means that the upper states are emptied even before the input pulse is over, thus shifting energy toward the leading edge of the pulse. Control over pulse length on a time scale, for example, of less than 10 ns requires that we tailor the line content of the pulse to achieve an optimum energy-extraction time profile. Preliminary experiments verified this picture of the energy-extraction physics; further work is progressing to elucidate the details.

BASIC RESEARCH: GROUPS P-2, P-3, P-8, P-9, AND P-10

C. D. Bowman, Associate Division Leader

The basic research groups of the Physics Division include Medium Energy Physics (P-2), Subatomic Research and Applications (P-3), Neutron Scattering (P-8), Accelerator Operations (P-9), and Condensed Matter and Thermal Physics (P-10). These groups, which take advantage of the unique resources of the Laboratory to expand our basic knowledge in nuclear and materials research and to strengthen the scientific base for Laboratory defense and energy programs, are also responsible for the establishment and operation of facilities required for present and future basic research at the Laboratory.

The Physics Division is strongly emphasizing development of research programs in condensed matter physics and related phenomena. Groups P-8 and P-9 are together developing the world's most intense pulsed source for neutron-scattering research. This facility is evolving from an effective combination of three facilities: the Clinton P. Anderson Meson Physics Facility (LAMPF), the Weapons Neutron Research Complex (WNR), and the Proton Storage Ring (PSR). Our present capability for neutron-scattering experiments will advance to the world-class category when the PSR becomes operational in 1985. Our current program and plans for developing a national center for neutron-scattering research are described in the research summary of Group P-8. Our capabilities in the area of synchrotron light are also advancing with the construction by this Laboratory of two beam lines at the National Synchrotron Light Source at Brookhaven. In contrast to the technique-associated emphasis in Group P-8, Group P-10 conducts a broadly based condensed matter research program using experimental facilities at Los Alamos and elsewhere to advance basic knowledge and to answer questions important to defense and energy programs. This broad base has served as fertile ground for a major program in the development of new heat engine concepts promising greater offering in heat transfer or heat conversion into work.

Several new ventures are under way in nuclear physics research. The work of P-3 includes a broad class of primarily nuclear phenomena with emphasis on neutron research from ultracold energies up to several hundred megaelectron volts, phenomena at the interface between nuclear and atomic physics, and weak interaction physics. The WNR/PSR facility offers world-class capability in many research areas related to nuclear physics, and development of these capabilities and techniques is under way by Groups P-3 and P-9. During 1983 a major development for weak interactions was the WNR-sited facility for neutrino research where a search for neutrino oscillation phenomena will begin soon followed by neutrino-nuclear cross-section measurements. Significant contributions in energy and defense-related nuclear research were completed in 1983 at the WNR.

Group P-2 research is focused on medium-energy nuclear physics using LAMPF primarily, but with extensive studies carried out at other world-class facilities. In addition to the significant research accomplishments reported here, P-2 is active in the planning and study for new capabilities at LAMPF, and much of the research carried out away from Los Alamos has prospective future capabilities at LAMPF as its focus.

The operation and improvement of basic research facilities for P-Division is the responsibility of P-9. The group operates the WNR and is heavily involved in upgrading the WNR facilities to accommodate the PSR beam and in extending to other capabilities such as the neutrino beamline referred to above. The group also is responsible for operation and improvements of the accelerator and associated facilities of the Ion Beam Facility (IBF), which includes three electrostatic accelerators. Research at the IBF includes defense and energy-related nuclear data measurements, basic nuclear physics studies, and increasing application of ion beams in materials science studies.

Medium-Energy Physics: Group P-2

J. M. Moss, Group Leader

The Medium-Energy Physics group has major programs in basic physics at LAMPF and at other accelerator facilities outside Los Alamos. The broad spectrum of the group's programs includes proton and meson physics, high-energy heavy-ion physics, and antiproton nucleus reactions. These cover most of the forefront research areas in nuclear physics ensuring our ability to attract top quality scientists to

Los Alamos. Programs such as antiproton physics also provide us with the experience and expertise that will be valuable in possible future Los Alamos efforts (that is, LAMPF II and antimatter applications).

P-2 also maintains a strong commitment to the Laboratory's programmatic efforts. During 1983 we contributed significantly to the Weapons and Whitehorse programs. We also participated in an important study of the technical feasibility of polarized targets in ICF and weapons applications.

The following contributions are examples of the group's accomplishments in basic and applied physics.

Coincident Neutron-Proton Emission from Proton Bombardment of ^{87}Sr and ^{91}Zr

A principal technique for determining the thermonuclear yield in a nuclear weapons test is to measure the production of neutron-deficient yttrium isotopes from successive (n,2n) reactions beginning with ^{89}Y . Of particular importance is the ratio of ^{87}Y to ^{88}Y produced in this fashion. A competing reaction to (n,2n), which is expected to be important in the yttrium isotopes, is the (n,pn) reaction. Because of the $N = 50$ neutron shell closure in this region and the subsequently large neutron-binding energies, proton emission can be very competitive with neutron emission (which is normally expected to dominate compound nucleus decay) and thereby can affect the yield of neutron deficient yttrium isotopes. This competition is expected to be most important for the $^{87}\text{Y}(n,np)$ and $^{87}\text{Y}(n,2n)$ reactions, because the energy interval in ^{88}Y over which proton emission, but not neutron emission, is allowed is about 6 MeV.

Up to now, interpretation of the isotopic ratios has depended solely on Hauser-Feshbach calculations, as there are no direct measurements of the $^{87}\text{Y}(n,np)$ reaction, and none is likely in the foreseeable future because of the short half-life (80 h) of ^{87}Y . Nevertheless, some experimental verification of the calculations of the effects of proton windows is desirable.

Another possibility for experimental verification of proton window effects is to perform (p,pn) reactions. In particular the $^{87}\text{Sr}(p,pn)^{86}\text{Sr}$ reaction closely parallels $^{87}\text{Y}(n,pn)^{86}\text{Sr}$ in its physics content, with both reactions involving the ^{88}Y compound nucleus and its decay modes, as shown in Fig. 43. Several additional factors also favor $^{87}\text{Sr}(p,pn)$ as a good simulation for $^{87}\text{Y}(n,pn)$. To reach the same excitation energy in ^{88}Y as produced by 14-MeV neutrons on ^{87}Y , we require incident protons of 16.7 MeV, which

Fig. 43. Energy-isotope diagram for the production and decay of ^{88}Y by 16.7-MeV protons on ^{87}Sr compared with 14-MeV neutrons on ^{87}Y .

are easily obtainable from the Van de Graaff accelerator. The ground-state spin of a ^{87}Sr target is $9/2^+$, considerably different from the $1/2^-$ ground state of ^{87}Y . However, during the time that the $^{87}\text{Y}(n,2n)$ reactions are taking place, most of the ^{87}Y that is bombarded by 14-MeV neutrons is expected to be in the $9/2^+$ isomeric state. Thus the angular momenta of states populated in ^{88}Y by neutron bombardment in a thermonuclear test should be similar to states populated in the $^{87}\text{Sr}(p,pn)$ reaction performed in the laboratory.

A proton window also exists in ^{91}Nb where the separation energy for protons is 6.9 MeV less than for neutrons. Although the immediate interest of this work was to study $^{87}\text{Sr}(p,pn)$ as a simulation of $^{87}\text{Y}(n,pn)$, the reaction $^{91}\text{Zr}(p,pn)^{90}\text{Zr}$ was studied initially to develop the experimental techniques. One of the advantages of zirconium is that low-contaminant zirconium targets are easier to fabricate than are yttrium targets.

The experiments consisted of bombarding targets of ^{87}Sr and ^{91}Zr with proton beams at several energies between 14.0 and 17.6 MeV (experiments were done at the tandem Van de Graaff accelerator). Protons and neutrons from the (p,pn) reaction were detected in coincidence using a silicon ΔE -E telescope for proton detection and a 3-in.-thick by 4-in.-diameter liquid scintillator neutron detector. The proton detector was placed at 135° to the incident beam, whereas neutrons were detected at 65° and 100° .

A typical two-dimensional spectrum of neutron-proton coincidences obtained at 16.0-MeV incident energy from a ^{91}Zr target is shown in Fig. 44. The spectrum of final states in ^{90}Zr is shown in Fig. 45(a), where the peaks correspond to the parallel bands from the two-dimensional spectrum in Fig. 44. A spectrum of final states in ^{86}Sr obtained from a similar two-dimensional spectrum of the $^{87}\text{Sr}(p,pn)$ reaction is shown in Fig. 45(b). In addition to the spectra of final states, the individual spectra of protons and neutrons populating the various final states are available from the measurements.

Using the measured double-differential cross sections and assuming isotropic angular distributions, we obtain total cross sections for the (p,pn) reaction populating states in ^{86}Sr and ^{90}Zr at a series of bombarding energies between 14.0 and 17.6 MeV. These results will be compared with Hauser-Feshbach calculations to determine whether proton window effects can be predicted reliably.

Pion Production in Proton and Antiproton Nucleus Collisions

High-energy heavy-ion collisions were proposed as a means of creating extremely hot nuclear matter. Matter in such a state is expected to exhibit properties very different from normal (cold) nuclei. An example is the much-discussed phase transition to quark matter expected at temperatures in excess of 100 MeV. We undertook a search for exotic states of nuclear matter with quite a different approach. The major aim of the program is to use the annihilation of antiprotons inside nuclei to achieve the heating effect of heavy-ion reactions. Previous theoretical work by P-2 physicists was the first to suggest that antiproton annihilation inside nuclei occurred with sufficient probability to be measured experimentally.

Our antiproton program at the Low-Energy Antiproton Ring (LEAR) at CERN began in November 1983, when we took our first set of measurements. Analysis of these data is in progress and will be reported soon. In this report we describe the spectrometer system used at LEAR and the results of the very important proton-nucleus program that is necessary for our understanding the antiproton-nucleus and heavy-ion reaction data.

In the past 3 years, we constructed and tested a novel spectrometer and developed an appropriate hardware-software data acquisition system for it. The spectrometer consists of a dipole magnet (Calliope), 80 cm in diameter, with a 7.5-cm pole gap, and a uniform field of up to 2.0 T. The target is at the center of the magnet, whose polefaces are surrounded by six detector assemblies. Each detector consists of two planes of x,y position-sensitive gas counters placed 10 cm apart, a Pilot-F ΔE scintillator, and one Cerenkov counter built of a 0.16-cm layer of Pilot 425 laminated on a 2.5-cm Lucite slab (see Fig. 46). The number of beam particles on target is counted by a 0.16-cm scintillation counter. The beam intensity is therefore limited to a few 10^6 p/s. This results in a produced pion rate well matched to the performance of the data acquisition electronics. This spectrometer can detect and analyze, over a range of scattering angles from 0 to 360° , mesons (and light ions) in the momentum range

Fig. 44. Two-dimensional plot of proton-neutron coincidences from the $^{91}\text{Zr}(p,pn)^{90}\text{Zr}$ reaction at 16.0 MeV.

$0.05 < p < 1$ GeV/c. The Camac-based data acquisition system is centered around a MODCOMP 7860 computer, with a variety of peripherals including a bulk memory processor with a 1-M-word histogram memory. The system can process a sustained event rate of 1 kHz, a typical event consisting of 25 to 30 16-bit words. The electronics and the computer are housed in a mobile trailer.

After debugging this system at LAMPF in 1981, we acquired some 330-MeV data there, in the summer of 1982. After moving the entire system to TRIUMF, we acquired data at 330-, 400-, and 500-MeV incident proton energy, in January 1983. These data were analyzed and the necessary software developed and debugged in the summer of 1983. The analysis is nearly complete and two comprehensive papers, one on the spectrometer system, the other on the $p+A \rightarrow \pi+X$ ($A(p,\pi)X$) reactions, are in progress. Some preliminary results are presented below.

Fig. 45. (a) Spectrum of final states in ^{90}Zr from the $^{91}\text{Zr}(p,pn)$ reaction at 16.0 MeV. (b) Spectrum of final states in ^{86}Sr from the $^{87}\text{Sr}(p,pn)$ reaction at 16.7 MeV.

Fig. 46. Schematic diagram of the Calliope spectrometer system.

In Fig. 47, we present our data on the π^+/π^- ratio, as a function of the incident kinetic energy. In Figs. 48 and 49, we show the integrated pion production cross section for π^+ and π^- , respectively. Our data were taken with targets of carbon and uranium. The data of Crawford et al.⁴ at 585 MeV are from carbon and lead targets, whereas Cochran et al.⁵ used carbon/thorium targets at 730 MeV.

These results, in good agreement with earlier work, give us confidence in the operation and understanding of the Calliope system and extend the existing data base toward the pion production threshold. Nuclear cascade calculations to compare with the data are in progress.

Fig. 47. Cross-section ratios for π^+ to π^- production. The circles are for a carbon target; the triangles, for a uranium target (lead at 585 MeV, thorium at 730 MeV).

Fig. 48. Total π^+ production cross section (see Fig. 47).

Fig. 49. Total π^- production cross section (see Fig. 47).

Measurements were carried out on various targets with tritium beams from the IBF and with tritium and deuterium beams using the Low-Energy Fusion Cross Section apparatus. Figure 50 shows the total cross section for the $D(t,\alpha)n$ reaction versus triton bombarding energy. These very precise data have relative errors between 0.5% at the high-energy end and 4.6% at the lowest energy, with an overall scale error of 1.3%. In Fig. 51 the data are replotted in terms of the astrophysical S-factor, from which the rapid Coulomb energy dependence is removed. The significance of these data may be seen in Fig. 52, in which comparisons to previous data sets are shown.

Fig. 50. Integrated (total) cross section for the $D(t,\alpha)n$ reaction vs triton (E_t) or equivalent deuteron (E_d) bombarding energy as measured in the present work. The unlabeled ticks on the cross-section scale are 2 and 5.

Fig. 51. The S function vs equivalent deuteron-bombarding energy for the present $D(t,\alpha)n$ data (points). Total errors are shown. Note the suppressed zero. The dashed curve is the result of a single-level fit.

Fig. 52. The S function vs equivalent deuteron-bombarding energy for the $D(t,\alpha)n$ reaction. The present data (solid points) are compared with all other known data below 140 KeV. Note the suppressed zero.

Neutron Physics

The combination of high neutron fluxes at the WNR and a bismuth-germanate detector system in Group P-3 makes possible (n,γ) reactions with neutrons and gammas in the 4- to 30-MeV range, where previous data are very sparse and data taking has been hampered by very low counting rates. Because the neutron is not affected by Coulomb distortion, this technique provides a powerful tool for the study of high-multipole giant resonances (collective states in nuclei with angular momentum greater than one). The first data obtained with this system are shown in Fig. 53 and 54.

Fig. 53. The 90° differential cross section for the $^{12}\text{C}(n,n'\gamma = 4.44 \text{ MeV})$ reaction and function of neutron energy.

Fig. 54. The 90° differential cross section for the $^{40}\text{Ca}(n, \gamma_0)$ reaction as a function of incident neutron energy.

Measurement of the $T(d, \gamma)^5\text{He}$ Cross Section at Low Energies

The $T(d, \gamma)^5\text{He}$ cross section at low energy is of considerable interest both because of a possible application as a "thermometer" for fusion reactors and because of implications regarding isospin invariance of the nuclear force when compared with the mirror system $^3\text{He}(d, \gamma)^5\text{Li}$. Not only because existing measurements differ by a factor of approximately 10 but also because of the paucity of information in them, the published results offer little convincing evidence that any of the data are correct.

We performed the experiment at the Los Alamos vertical Van de Graaff accelerator using a pulsed deuteron beam incident on a thick tritium gas target. In the experimental arrangement shown in Fig. 55, the 0° neutron yield from the $T(d, n)^4\text{He}$ reaction was measured simultaneously with the 90° gamma-ray

Fig. 55. Experimental arrangement for the $T(d, \gamma)^5\text{He}$ measurements.

yield from the $T(d,\gamma)^5\text{He}$ reaction. Time-of-flight (TOF) and pulse-height data were accumulated by the Van de Graaff Modcomp IV computer system in event-by-event mode. A typical gamma-ray spectrum is shown in Fig. 56. Measurements were taken with three different incident energies in order to integrate over different parts of the $3/2^+ T + d$ resonance at 110 keV. We also replaced the tritium with ^3He and obtained data on the $^3\text{He}(d,\gamma)^5\text{Li}$ reaction.

Data analysis of this experiment is still under way, but preliminary results indicate that the $T(d,\gamma)/T(d,n)$ branching ratio is approximately 5×10^{-5} and that the $T(d,\gamma)/D(^3\text{He},\gamma)$ branching ratio is unity, in agreement with that expected from charge symmetry.

Investigation of Fine Structure in the M1 Region of ^{90}Zr

Magnetic dipole (M1) excitations in closed-shell nuclei, such as ^{90}Zr and ^{208}Pb , should be very simple to understand. In ^{90}Zr , for example, we expect to find a single state of $\sim 9\text{-MeV}$ excitation energy that carries all the electromagnetic decay strength allowed by the M1 sum rule. Experiment findings, however, are extremely confusing. In no heavy nucleus is any state found with a sizable fraction of the M1 sum rule. In ^{90}Zr the situation is particularly confusing. Recent measurements of cross-section angular distributions for 200-MeV proton scattering revealed a 2-MeV-wide bump without clear fine structure at about 9-MeV excitation; it appears to exhaust about half of the expected M1 strength. However, a detailed high-resolution (40-keV) study of electron scattering at 165° identified only a few well-separated M1 states amid a very large number of M2 states.

To help resolve the apparent discrepancy between proton and electron scattering, we made high-statistics measurements of the cross section for the $^{90}\text{Zr}(p,p')^{90}\text{Zr}$ reaction at 318 MeV. The data were taken at the high-resolution spectrometer at LAMPF at scattering angles of 2.75° and 4.25° . The energy resolution (60 keV) is similar to that of the Orsay work, but the background at low excitation energy is dramatically improved. A spectrum for the 0.4° -wide angular bin at 2.2° is illustrated in Fig. 57 (top). The 9-MeV region is shown expanded in the bottom figure for the complete 1.6° -wide angular bin at 2.75° . Clearly identifiable narrow peaks can be observed in the expanded figure; these peaks can be traced over the entire angular region. This fine structure was not observed in the previous proton work and seems in better qualitative agreement with (e,e') spectra. However, detailed analysis of excitation energies and angular distribution data does not confirm this agreement. Eight-point angular distributions were obtained by dividing the data at each angle into four angular bins. Peak sums were obtained either by summing over 300-keV-wide bins or by peak fitting; in each case, a suitable background was subtracted. Comparison of these distributions with DWIA calculations indicates that, with some exceptions, excitation of the 9-MeV bump at the most forward angles is dominated by $L = 0$ transfer, in

Fig. 56. Gamma-ray pulse-height spectrum obtained in the $T(d,\gamma)^5\text{He}$ experiment.

Fig. 57. Spectrum of protons inelastically scattered from ^{90}Zr ; note that background due to the tail of the elastic scattering peak is small (top). A similar spectrum expanded in the 9-MeV region. The fine structure observed between 8 and 10 MeV can be followed over the entire region (bottom).

agreement with (p,p') . Possible excitation of some M2 states is suggested by some flat or rising cross sections at larger q , but the contribution of these apparent 2^- states at the smallest angles is small. The differences between (p,p') and (e,e') reactions on ^{90}Zr thus persist and are as yet unexplained.

Subatomic Research and Applications: Group P-3 G. Stephenson, Group Leader

The efforts of Group P-3 can be divided roughly into several main areas: weak interaction physics involving experimental techniques of both particle physics and nuclear physics; low-energy nuclear physics reactions with some applications to astrophysics, fusion energy physics, and weapons physics; high-energy neutron-nuclear physics; studies of the behavior of materials under extreme conditions of pressure and temperature available at the Nevada Test Site; and a developing effort in the interaction of optical radiation with nuclear transitions. Some highlights are given below.

Weak Interactions

Three major experimental efforts progressed greatly during the past year.

1. The program to measure electron-neutrino scattering from electrons [in collaboration with the University of California (UC) at Irvine and MP-Division of the Laboratory] is nearing completion with serious data being taken in the fall 1983/winter 1984 running cycle.
2. Preliminary studies of the dissociation of hydrogen molecules into atomic hydrogen are completed, allowing final designs for the full measurement of the beta decay of atomic tritium. This experiment should provide the world's most sensitive probe of the mass of the electron anti-neutrino and will provide a definitive statement on existing claims of a neutrino mass near 30 eV. Data taking should begin in the next fiscal year.
3. The neutrino program made great strides with the construction of Line E at LAMPF (Fig. 58). With a detector built by Group P-14, personnel from Groups P-3 and P-14, MP-Division, UC at Riverside, UCLA, UNM, Temple, and Valparaiso will collaborate to take muon-neutrino nucleus cross-section data and look for large-amplitude neutrino oscillations next summer.

Fig. 58. Layout of WNR/PSR complex showing location of neutrino beamline (Line E), neutrino production target, pion decay channel, shielding, and neutrino detector.

At the IBF, in a related measurement that is important to the understanding of nuclear parity violation, the beta decay of the 0^+ ground state of ^{16}C to the 0^- 120-keV state of ^{16}N was completed. Both radioactive target and beam were used in the collaborative experiment with Texas A & M and Argonne National Laboratory. The branching ratio to this final state was only 20% of that expected.

High-Resolution Nucleon-Induced Charged-Exchange Reaction Studies at 800 MeV

Nucleon-induced charged-exchange reactions at bombarding energies of several hundred megaelectron volts have indicated that extremely interesting and, at present, poorly understood processes are involved. As an example, in (p,n) reactions the strength of Gamow-Teller (GT) transitions may be computed from a simple sum rule. Recent data near 200 MeV indicate that approximately 30% of the expected GT strength is missing. One exciting possibility is that the GT strength is "quenched" because of appreciable delta-isobar, nucleon-hole (delta-hole) components in the low-lying GT levels. Such a theory, if correct, implies that nucleon excitations such as the delta, which were considered too high in energy to be important in the low-energy domain, must be considered. Alternative conventional nuclear structure effects also were proposed to account for the GT quenching effect. Our studies of (p,n) reactions at the WNR will permit a search for the transfer of GT strength directly.

To study this and other aspects of nucleon-induced charge-exchange, we are using a 213-m-long zero-degree reaction angle flight path at the WNR, the only facility in the world capable of high enough neutron energy resolution to permit the observation of nuclear structure effects at 800 MeV. Preliminary results thus far obtained for (p,n) indicate that we can obtain information addressing four areas of interest: (1) excitation of discrete levels leading to unique information on the isovector and isovector spin-flip parts of the effective N-N interaction, (2) the nature of the Pauli-blocked quasi-elastic knock-on peak, (3) the nature of the broad resonances associated with the delta and possible implications for delta-hole configurations in nuclear spectra, and (4) the excitation of charge exchange analogs specifically using (n,p) reactions.

As an example of the above, we compared our spectra for $^{13}\text{C}(\text{p},\text{n})$ shown in Fig. 59 with those available at lower energies and conclusively identified Gamow-Teller and Fermi transitions, thus greatly extending the energy range over which these transitions have been studied. We summarize these results in a publication we are preparing for *Physical Review Letters*.

To explore (p,n) reactions in more detail, we must obtain angular distribution data. During early 1984, we plan to install a beam swinger to change the angle of incidence of the proton beam and thereby obtain angular distributions using the existing equipment.

Fig. 59. An 800-MeV $^{13}\text{C}(\text{p},\text{n})$ TOF spectrum at $\theta = 0^\circ$. Overall resolution is approximately 2.5 MeV (FWHM). Arrows indicate expected locations of peaks observed in 160-MeV spectrum shown in the inset. The smooth curves indicate best fits to the background and peaks.

Neutron Scattering: Group P-8
Richard Silver, Group Leader

Group P-8 is responsible for condensed matter research using the Laboratory's new pulsed spallation neutron source, the world-class WNR/PSR facility. Major progress in 1983 included the initiation of a National User Program, major construction of new instrumentation, exciting developments in condensed matter science, and the first significant effort toward organizing conferences to stimulate the field of pulsed neutron scattering. Some highlights follow.

National User Program

The neutron-scattering group announced, in 1983, a formal National User Program at the WNR/PSR facility. This opened the use of the facility to the national and international scientific communities in solid-state physics, chemistry, materials science, and biology. Proposals for the use of neutron-scattering instrumentation are to be reviewed by a nationally appointed Program Advisory Committee (PAC) at semiannual meetings. After considering the level of scientific excellence and optimal use of WNR/PSR characteristics, the PAC will allocate two-thirds of the available neutron-scattering beam time (presently 60% of the LAMPF operating schedule). The remaining one-third of the beam time will be reserved for Laboratory discretionary use including programmatic research and instrument development. The first PAC meeting at Los Alamos was held June 6, 1983. In the initial solicitation, 24 proposals were received and 15 were allocated beam time. Presently the PAC is shared jointly with the IPNS program at Argonne National Laboratory.

Neutron-Scattering Instrument Development

To accommodate the user program in 1983, Group P-8 exerted a major effort to build two well-engineered instruments, the Be-BeO Filter Difference Spectrometer (FDS) and the Single Crystal Diffractometer (SCD). The FDS, shown in Fig. 60, is used for chemical spectroscopy, localized modes, and phonon density-of-states measurements. The new FDS features separate cryostats for cooling the two filter sections to improve their transmission, new filter sections and collimation to increase the solid angle of the detection system, and individual counter electronics to aid in the discrimination against spurious scattering processes. Compared with the original prototype instrument, it offers four times the data rate and an even higher signal-to-noise ratio. The performance achieved was generally very good, but problems remained in electronic noise in detector electronics and background from inadequate detector shielding, which we will address in 1984). The SCD, shown in Fig. 61, uses the Laue-TOF technique. It offers a novel two-axis goniometer, which is adequate to cover most of reciprocal space in a TOF instrument. Compared with the original prototype instrument, the new SCD has much higher signal to background, much more accurate positioning of the crystals, allows routine low-temperature structural analysis (15 K to 300 K), accommodates rapid changes in the instrumental resolution, and offers much greater versatility. The latter was demonstrated in some novel high-pressure experiments we discuss below.

The experience of building two well-engineered instruments for the user program was particularly valuable in estimating the manpower and costs required for the full instrument development program at the WNR/PSR facility. The experience of FY83 showed that each instrument required approximately \$500 thousand, two scientists, one designer, one mechanical technician, and one-half electronics technician to be brought into useful operation. As later WNR instruments will be increasingly sophisticated, these figures are the lower bounds for probable costs. Additional experience was gained in procurement, dealing with Laboratory service organizations, and scheduling. A project management system may be required for more efficient management in the future.

We developed four other major instrument projects in FY83. (1) A prototype Constant Q Spectrometer (CQS) was brought into initial operation. The CQS, shown in Fig. 62 will serve in the study of elementary excitations, such as phonons and magnons, in single-crystal samples. Effort in 1983 was

60. The Filter Difference Spectrometer (FDS).

Fig. 61. The Single Crystal Diffractometer (SCD).

Fig. 62. The Constant Q Spectrometer (CQS).

expended on improving the collimation and shielding around the sample, analyzer, and detector area and on collecting initial data sets to use in testing on-line data analysis software currently under development. (2) A prototype Liquids, Amorphous, and Special Environment Diffractometer (LASED) was brought into initial operation. The LASED, shown in Fig. 63, is optimized to low-angle diffractive scattering with epithermal neutrons at low resolution. This is particularly important in liquid diffraction for the elimination of inelasticity corrections (Placzek effects) and for powder diffraction from magnetic structures. Such an instrument cannot easily achieve low background in low-angle scattering, but this was accomplished by a novel shielding arrangement with extensive B_4C shielding around the sample

Fig. 63. The prototype Liquids, Amorphous, and Special Environment Diffractometer (LASED).

and detectors, as well as incorporation of B_4C into the collimator materials. (3) An Electron Volt Spectrometer (EVS) that uses the nuclear resonance filter difference method was developed jointly with the Rutherford Appleton Laboratory and brought into initial operation at the WNR. This instrument, shown in Fig. 64 differs somewhat from prior filter difference experiments at the WNR as it uses fixed filters in both the incident and secondary beams to eliminate elastically scattered neutrons from the same time channels where inelastic events are to be observed. Offsetting this advantage, however, is the lack of secondary collimation and the location of the analyzer and fixed secondary filters in the main neutron beam. Experiments with this arrangement gave results as predicted from simulations for samples such as ZrH_2 , but the attempts to carry out true measurements of electronic transitions were unsuccessful. (4) the Neutron Powder Diffractometer (NPD), shown in Fig. 65, received a new sample environment can and additional detectors.

Fig. 64. The Electron Volt Spectrometer (EVS).

Fig. 65. The Neutron Powder Diffractometer (NPD).

These developments brought the number of neutron-scattering instruments at the WNR facility to six. The present arrangement of instrumentation at the WNR is shown in Fig. 66.

Detector development in 1983 included the first true multifield test of the Anger Camera concept with fast (400-ns deadtime) electronics. Mechanical, optical, and electronic assemblies were completed, and initial results at the Omega West Reactor showed that the detector encoding concept was valid. However, full evaluation of the detector will take a few more months.

Electron-volt spectroscopy development included the publication of several instrument papers on general aspects of the nuclear resonance filter difference technique and experimental results from the WNR. Also, considerable theoretical work was completed on the double-difference method for improving the resolution of this technique.

Condensed Matter Research

A highlight of 1983 was the completion of work on the structure of the first complex that reversibly binds molecular hydrogen, $\text{W}(\text{CO})_3(\text{PPr}_3)(\eta^2\text{-H}_2)$. It is normal in the process of the catalysis of H_2 to form species so that a hydrogen molecule, as it approaches a metal complex, will dissociate; the hydrogen atoms will bind to two separate sites in the complex. This will, in turn, release the hydrogen atoms to bind to other radicals in a subsequent step of the catalysis to form new chemical products. The initial step, the approach of the hydrogen molecule to the metal complex, has not been observed. However, in 1980 scientists in Group INC-4 at Los Alamos synthesized a new material that reversibly

Fig. 66. Arrangements of WNR instrumentation.

bound molecular hydrogen. A variety of spectroscopic and x-ray diffraction measurements gave indirect evidence that a hydrogen molecule was bound in an activated state to the complex. However, only a neutron diffraction measurement could be definitive because neutrons were the most sensitive probe for hydrogen in materials. Experiments were carried out with the prototype single-crystal diffractometer at the WNR facility in 1982, and the analysis, which revealed the structure shown in Fig. 67, was completed in 1983. The hydrogen molecule was bound with a longer H-H distance than in the free molecule. As this was the first new structure determined with the SCD and as low-temperature capability was not available at the time, there was considerable controversy about its validity. The experiment, which was repeated at the HFBR reactor in 1983, confirmed the original WNR structure. Most recently, low-temperature data, taken on the new SCD in 1983, are currently being analyzed to further refine the structural parameters. Thus, in 1983 the WNR facility played a seminal role in revealing new information on the catalysis process.

The SCD was also used to solve a long-standing puzzle about ReO_3 . This material has the unusual property of undergoing a "compressibility collapse" at 5.2 kbar to one-tenth the compressibility at ambient pressure. The structure of the high-pressure phase was difficult to determine with X-rays because of the large difference in x-ray scattering cross sections for Re versus O. A time-of-flight experiment at the WNR allows data to be collected by varying the wavelength rather than the scattering angle, which makes this a particularly valuable method for special environments. The use of an area detector still allows many Bragg reflections to be collected from a single orientation of the crystal. Experiments conducted at the WNR with Sandia National Laboratories personnel revealed the structure shown in Fig. 68 where the unit cell has doubled and the ReO_3 octahedra have rotated compared with the zero-pressure structure. This structure confirmed indirect evidence obtained by many other measurements and showed that the WNR is particularly advantageous for high-pressure diffraction experiments on single crystals. Data, which have been collected on other samples at high pressure, are being analyzed.

Collaborative work with Sandia National Laboratories explored the hydrogen site occupancy in rare-earth metal dihydrides. Hydrogen and several rare-earth metals form solid solutions with an fcc calcium fluoride structure. While the hydrogen prefers to go into tetrahedral sites (t-sites) when the metals are loaded to the dihydride composition, several experiments have shown a partial occupancy of octahedral sites (o-sites) before complete filling of the t-sites. Experiments by a variety of techniques verified approximately 10% occupancy below 300 K in YH_2 . Because entropy arguments lead us to expect that

Fig. 67. Structure revealed by analysis of experiments in the SCD at WNR, in 1982.

Fig. 68. (a) Ambient pressure ReO₃ packing, showing linear Re-O-Re chains. (b) High-pressure ReO₃ structure, showing "hinging" at the oxygen atoms in the Re-O-Re chains.

the o-site occupancy would increase with temperature, we are surprised to find only 1% occupancy at 920 K. We conducted inelastic neutron-scattering and neutron-diffraction measurements with the FDS and NPD over a sufficiently wide temperature range to clarify this situation. An example of inelastic data is given in Fig. 69. This good separation between t- and o-site peaks allows the relative occupancy to be determined with good accuracy. NPD data generally confirm the INS results. Figure 70 shows the fraction of hydrogen atoms on o-sites versus temperature for YH₂. The theoretical model that describes these data includes proton-proton interactions and the relative entropy of o- and t-sites. With increasing temperature, entropy is increased by the movement of o-site H's to t-site H's because t-site occupancy allows the lattice to expand whereas o-site occupancy causes the metal lattice to contract.

Fig. 69. Inelastic data sample.

Fig. 70. Fraction of hydrogen atoms on O-sites vs temperature for YH_2 .

The FDS served in three other projects. (1) The first successful studies of the vibrational spectra for molecules chemisorbed on surfaces (in collaboration with Harwell). The INS data were taken of hydrogen on two types of nickel powder, Raney nickel and coprecipitated nickel. The former is a common catalyst. The INS spectra show pronounced differences that are related to the absorption site geometries and/or their distribution. (2) The vibrational spectra of hydrogen, deuterium hydride, and ethylene adsorbed in the cage-like sites of a zinc zeolite were studied. Again, after intensity calculations are complete, these data should provide information on the absorption site geometries of the molecules in these catalysts. (3) To determine H-bonding character in PbO_2 battery plate material, we measured the positions and intensity of hydrogen vibrational peaks after chemical recycling.

The LASED instrument, with its low-angle diffraction capability and its very high count rates, was used to confirm, by powder diffraction, the antiferromagnetic structure of UGa_3 and the ferromagnetic structure of UGa_2 . Also experiments were conducted on residual strains in heavily cold worked aluminum and brass, to study amorphous Zr_2PdH_x , to resolve ambiguities in other measurements of hydrogen site geometries, to develop a high-pressure diffraction apparatus, and to demonstrate (by a study of the well-known structure of amorphous SiO_2) that the instrument was indeed well suited to diffraction measurements of amorphous materials. An attempt to use the nuclear resonance filter difference method to study several hundred millivolt multiplet transitions on PrO_2 was unsuccessful.

Conferences and Meetings

The first meeting of the PAC was held June 6, 1983, at Los Alamos. On September 9 and 10, 1983, "Frontiers in Condensed Matter Physics with the WNR/PSR Pulsed Neutron Source," was chaired by R. Birgeneau of MIT. The workshop brought together leaders of the neutron-scattering field to discuss the most exciting current topics in condensed matter physics and how experiments at the WNR could help. A workshop on November 7 and 8, 1983, was held in collaboration with LS-Division to discuss

biological applications of the WNR/PSR facility. Planning was finalized for a large workshop, "High-Energy Excitations in Condensed Matter," to be held in February 1984. This HEECM workshop will address inelastic scattering with the high epithermal flux of new pulsed neutron sources and the high intensity of new synchrotron light sources.

Experimental Halls Proposal

A proposal to expand the experimental halls at the WNR facility was prepared in collaboration with Group P-9. The proposal, which incorporated the expansion recommendations of the Brinkman II panel report, also included funds for a new computer system and for instrumentation. This was reviewed by an external review panel, chaired by M. Rowe of NBS in early February 1983 and by a DOE construction review panel in August 1983.

Accelerator Operations: Group P-9

R. Woods, Group Leader

The operation, maintenance, and development of the Weapons Neutron Research/Proton Storage Ring (WNR/PSR) facility and Ion-Beam Facility (IBF) are the purview of Group P-9. At the WNR/PSR, preparations continue for the installation of improvements to the WNR for operation at the 100- μ A proton beam current level from the PSR. Because neutrons from the spallation process are our primary product, we emphasize understanding this process in heavy metal targets by using both an experimental program and computer-based theoretical models. The PSR time schedule calls for final installation starting October 1, 1984, with commissioning of the PSR and upgraded WNR in the spring of 1985. The WNR operated routinely from September through December 1984 with 97% availability. The two Van de Graaff accelerators at the Ion-Beam Facility were available continuously for experiments when WNR did not operate and on an intermittent basis otherwise. Ion beams from throughout the periodic table were produced for programs in materials-near-surface analysis, neutral beam dynamics, cross-section measurements, detector calibrations, and many other diverse applications. The continuing support and development of advanced computer-based data acquisition and reduction systems remain a primary responsibility at both facilities. The latest system will be VAX based with a FASTBUS interface including custom modules to handle average data rates of 10 MHz. The prototype hardware is scheduled for on-line check-out in September 1984.

WNR/PSR Proton Beamline

The existing proton beam transport system of the WNR delivers a beam to the PSR, which then ejects it back into the WNR for neutron production as shown schematically in Fig. 71. Several systems in the existing WNR facility must be upgraded to handle the increased power and neutron flux at the 100- μ A level of the PSR design. The present operation at WNR at 10 μ A uses the H^+ beam from LAMPF. The PSR injection scheme requires H^- beam, which also dictates certain changes in the WNR. Construction project funding from Basic Energy Science at DOE will cover these required improvements to the proton beam transport line, the target-moderator-reflector (TMR) system, and shielding additions near the target.

Hands-on maintenance of the proton beam line components is essential. The activation of such components must be kept low by keeping the proton beam losses to a minimum. The emittance characteristics of the H^- beam at 100 μ A and the acceptance characteristics of the PSR required exhaustive computer calculations using the beam optics code TRANSPORT to indicate which existing beamline components should be moved or replaced with larger aperture units and where additional optic elements should be located. The physical size and magnetic strength of beamline components are further dictated by our need to keep field strengths below 4 kG to prevent stripping of the H^- beam to

Fig. 71. Schematic of existing proton beam transport system, WNR.

H^0 . There are time-sharing modes where H^- beam from LAMPF will be going to the PSR and either to the WNR directly or to a neutrino experiment area. To permit this, a pulsed kicker magnet and stripper foils will be installed.

Neutron Target

The increased power from 10 to 100 μA must be dissipated in the new design of the target-moderator-reflector (TMR) system. We are also planning a depleted uranium target and designing to avoid precluding the installation of a boosted target in the future. The new concept for the TMR is shown in Fig. 72. The concept is a split target with a void between and with moderators located around this void in an arrangement termed the "flux trap geometry." The neutron flight paths that view these moderators thus will not "see" the neutron target itself. This significantly reduces the background of unwanted high-energy neutrons. The existing WNR flight paths will view these moderators. The upper target will be provided with wing moderators that can be viewed by future flight paths. In this design the target and moderators are surrounded by a 1-m-diam cylinder of material that acts to reflect neutrons back into the

Fig. 72. New TMR concept.

moderators and also serves as additional biological shielding. The installation of a depleted uranium target in the spring of 1985 will give a factor of ~ 2.0 in useful neutron production over our present system. A liquid hydrogen moderator also will be installed at that time to provide a source of cold and ultracold neutrons.

The increased neutron flux resulting from these improvements necessitates increased shielding above the WNR target to protect radiation-vulnerable equipment above. Another 2 ft of iron shielding will be provided for this purpose; additional shielding and a water-cooled beam stop will be provided below the WNR target.

Fertile-to-Fissile Conversion Studies

The optimization of the TMR system involves an experimental and a computational effort that is part of the Los Alamos Fertile-to-Fissile Conversion (FERFICON) program. The experimental program has measured axial distributions of fertile-to-fissile conversion (^{232}Th to ^{233}U and ^{238}U to ^{239}Pu), spallation, and fission products for thick thorium and depleted uranium targets bombarded by 800-MeV protons. Each measured axial distribution is integrated to get the total formation of the individual products. Uranium-233 and ^{239}Pu production was determined by measuring the amount of ^{233}Pu and ^{239}Np produced respectively; the number of fissions was deduced from fission product mass-yield curves. These measurements are "clean" integral experiments, and the data are relevant to the spallation neutron source development, accelerator breeder technology, and validating computer codes used in these applications.

At Los Alamos, we assembled and integrated into a package, the following state-of-the-art Monte Carlo codes for use in spallation physics computations: the Oak Ridge National Laboratory (ORNL) code HETC for particle transport >20 MeV and the Los Alamos code MCNP for neutron and photon transport <20 MeV. The Los Alamos code HTAPE is used to analyze the Monte Carlo results. The ORNL HETC version includes high-energy fission effects for $Z \geq 91$. Also operational is the Rutherford Appleton Laboratory (RAL) HETC version, which allows high-energy fission with essentially no restriction on Z . With MCNP, continuous-energy Monte Carlo calculations are done with pointwise ENDF/B-V cross sections.

In our calculations, a precise mockup is made of target geometry, target canister, proton beam window, and air paths. The measured proton beam profiles are simulated with concentric ring sources, and the proton fraction in each ring is obtained from measured distributions.

The thorium target was composed of 19 rods in a cluster; the depleted uranium target, of 37 rods. We explicitly measured the axial distribution of products by selectively sampling various planes perpendicular to the target axis; the radial integral for each plane is performed by combining sampling foils from the plane. The conversion-measurement targets and foil-loading schemes are illustrated in Fig. 73.

Fig. 73. Illustration of cluster targets used in the conversion measurements, the location of the foils in an array, and the foil positions within a rod.

For the thorium target, the yields of 39 isotopes were measured either independently (produced by direct formation) or cumulatively (produced by direct formation plus the beta-decay of predecessors). The depleted uranium target measurement has yielded (to date) either independent or cumulative yields of 14 isotopes; we will attempt to extract more results from our depleted uranium measurement. Some preliminary experimental data are compared with calculated predictions in the table. Shown are results of the calculations for the RAL high-energy fission model with a level density parameter (B_0) of 8 MeV rather than 14 MeV (which is the RAL recommended value).

These results are used to validate the computer codes that predict the performance of our TMR systems and are crucial to the neutronic optimization of the WNR/PSR facility.

Materials Science at the Ion-Beam Facility

Materials-near-surface analysis with ion-beam probes constitutes a large and growing program at the Ion-Beam Facility (IBF). This program uses the interaction of the ion beam with the surface of a material to gain information about the surface, such as its elemental analysis, its crystalline structure, or its thickness.

Two fundamental techniques are used for materials analysis. One is Rutherford backscattering (RBS). This technique simply measures the energy of ions that are Coulomb scattered from a surface. The thickness of a coating or a plating can be determined by the energy loss of the backscattered ions. An example of this technique is shown in Fig. 74 where the thickness of a bismuth layer on a steel backing is measured. The uniformity of the coating can be measured with a precision of better than 1%; an individual measurement takes only a few minutes. This type of measurement is of great importance to preshot diagnostics for the weapons program.

The second method is particle-induced x-ray emission (PIXE). In this technique the characteristic x rays produced by the ion-beam bombardment of the surface are detected and analyzed. These x rays are used to detect trace elements in amounts as low as 10 ppm. One of the applications of this technique is the determination and distribution of radiochemical detectors in uranium components.

A very powerful analytical tool results from the use of the PIXE technique with the proton microprobe. The Los Alamos microprobe is uniquely designed to produce a large beam current density in the focused spot. The spot size can be as small as several microns in diameter. With the PIXE technique elemental analysis can be performed on a very small spatial scale. Microprobe-PIXE analysis has been used with geologic and meteoritic samples. An example of such an analysis is shown in Fig. 75.

Preliminary Experimental Data Compared with Calculated Results for the Conversion Measurements.

	Experiment	Calculation		
		RAL ($B_0 = 8$ MeV)		ORNL ($B_0 = 10$ MeV)
		Without High-Energy Fission	With High-Energy Fission	With High-Energy Fission
Thorium Target				
^{233}U Production (atm/p)	1.25 ± 0.06	1.248 ± 0.008	1.267 ± 0.007	---
Number of Fissions (fiss/p)	1.56 ± 0.25	0.486 ± 0.004	1.543 ± 0.006	---
^{95}Nb Production (atm/p)	0.068 ± 0.003	0.0265 ± 0.0005	0.0551 ± 0.0009	---
^{205}Bi Production (atm/p)	0.0056 ± 0.0003	0.0362 ± 0.0010	0.0077 ± 0.0004	---
^{227}Th Production (atm/p)	0.046 ± 0.002	0.0658 ± 0.0016	0.0221 ± 0.0007	---
Depleted Uranium Target				
^{239}Pu Production (atm/p)	3.81 ± 0.19	3.541 ± 0.028	3.875 ± 0.031	4.133 ± 0.032
Number of Fissions (fiss/p)	5.59 ± 0.56	3.660 ± 0.030	6.144 ± 0.037	6.989 ± 0.041
^{99}Mo Production (atm/p)	0.319 ± 0.014	0.223 ± 0.004	0.318 ± 0.005	0.367 ± 0.006
^{237}U Production (atm/p)	0.95 ± 0.05	0.815 ± 0.012	1.024 ± 0.014	1.325 ± 0.016

Fig. 74. RBS spectrum from a bismuth coating on steel.

This figure shows a portion of a PIXE spectrum from a grain of the mineral sphalerite (zinc and iron sulfide) in the E3 chinese meteorite "Quinzhen." The abundances of some of the trace elements are given in the figure. Strontium and rubidium are not commonly found in this mineral. Measurements such as this one conducted by INC Division in collaboration with E Division, the California Institute of Technology, and the California State University at Fullerton provide important information for cosmology. The microprobe, which uses the proton beam from the vertical accelerator, was adjusted to produce a beam spot size of 25- μm diameter with a current of 7.5 nA. The sphalerite grain was approximately 50 μm in diameter.

The ion-beam materials analysis program is continuing to grow. In anticipation of this large program, an accelerator control console and a data acquisition system have been added to the second floor experimental area.

Fig. 75. PIXE spectrum of a 50- μm -diameter sphalerite grain in a meteoritic sample.

Condensed Matter and Thermal Physics: Group P-10

W. E. Keller, Group Leader

Research programs in Group P-10 encompass rather wide-ranging topics in condensed matter and thermal physics, selected for their relevance to the Laboratory's mission in significant scientific areas. Topics include fundamentals of heat engines/refrigerators; high-pressure physics and chemistry; liquid helium hydrodynamics and phase dynamics; solid-state physics, with emphasis on superconductivity and magnetism; and characterization of spin-aligned atomic hydrogen and tritium systems, as well as condensed molecular tritium systems.

Intrinsically Irreversible Heat Engines

Intrinsically irreversible heat engines require irreversible processes to function. In particular, we consider situations where the irreversibility necessary to produce work flow introduces a phasing between two variables, for example, pressure and velocity, in a reciprocating system. Because such processes are analogous to certain irreversible processes in nature, we also call these engines "natural engines." Additionally, these engines are characterized by simplicity; it is therefore appropriate to exploit the new principles and concepts we are developing for practical applications, especially in the area of thermoacoustics. At Los Alamos, we are investigating gas acoustic cooling devices (refrigerators) and liquid/metal acoustic prime movers. In both instances, the fluid is the primary thermodynamic medium and a stack of solid insulating sheets is the secondary medium. We call the latter a "thermoacoustic couple," because its presence causes the two mediums to execute reciprocating motion with respect to one another; under these conditions heat is exchanged between the two media as a result of the natural, irreversible process of heat conduction across a finite temperature gradient. When this temperature gradient is defined as $\nabla_x T \equiv \Delta T_A / \Delta X$ (that is, the ratio of the adiabatic temperature difference generated in the fluid by the acoustic displacement to the length of the acoustic displacement), the two engine modes, refrigerator or prime mover, are distinguished by whether $\nabla_x T$ is less than or greater than some critical value dependent upon the heat transfer between the two media.

Advances in Gas Engines. In the most recent gas acoustic refrigerator that we built, the primary medium is helium gas at 10 bar, and the secondary medium is a roll of Kapton film (~ 3.75 -cm diam by ~ 7.5 -cm length) with successive layers uniformly spaced. Each end of the roll connects with a heat exchanger; as a temperature difference is acoustically generated across the roll, one exchanger can be labeled "hot" and the other "cold." The roll-exchanger assembly is placed in a tube appropriately close (~ 3.5 cm) to an acoustic driver (loudspeaker) that forms one end of the tube; the other end of the tube opens to a volume (~ 1 l) serving as a gas spring to complete the resonant acoustic system. In operation, the loudspeaker performs work on the helium gas, pumping heat from the cold heat exchanger at T_{COLD} to the hot heat exchanger at T_{HOT} (at the driver end). Results of a test run with the apparatus are shown in Fig. 76, where T_{HOT} and T_{COLD} are shown as a function of time t after the acoustic power was turned on. At $t = 200$ min, where $T_{\text{HOT}} - T_{\text{COLD}} \approx 80^\circ\text{C}$, the cooling power at the cold exchanger is estimated to be 0.6 to 0.8 W. (The nonmonotonic behavior of T_{HOT} is due to the initiation of water cooling of the driver some minutes after the test began.) Although the model discussed here is only the first form of an acoustic cooling apparatus upon which we can make quantitative measurements, the cooling results are truly dramatic. A number of improvements to the model are under way, and we expect to obtain substantially better refrigeration than is depicted in Fig. 76.

Liquid Sodium Engine. Figure 77 shows schematically the configuration of an acoustically driven prime mover using liquid sodium as the primary medium. Here the introduction of heat $\dot{Q}_H$ at the two ends and the presence of the thermoacoustic couples, S_1 and S_2 , produce temperature gradients along the couples and acoustic oscillation of the fluid in the central portion between the couples. Because liquid sodium is a good electrical conductor, magnetohydrodynamic means may be used to extract electrical energy directly from this device, which could have a number of exciting and significant practical

Fig. 76. An example of the change of temperature with time (plotted on a logarithmic scale) for the acoustic cooling engine. All parts except the driver were thermally insulated with about 15 wrps of superinsulation and contained in a space evacuated to a pressure of about 10^{-3} torr.

applications. Such possibilities are enhanced by the specific properties of liquid sodium that are desirable for thermoacoustic engine operation, such as a low ratio of kinematic viscosity to thermal diffusivity, a large thermodynamic activity, and the potential for large acoustic power densities. We have, therefore, established a program to design, construct, and test a liquid-sodium acoustic engine configured to be a prime mover. To begin the design, we first required an understanding of liquid thermoacoustics, and this we achieved by extending Rott's theory⁶ of gas thermoacoustics. On the basis of our liquid studies, we developed numerical algorithms enabling us to design the engine. Calculations on our model, which take into account viscous and thermal losses, indicate that an engine with a 10-cm diam by 1-m length could produce 2 kW with an efficiency of 19% when operated at 1 kHz, with an acoustic pressure amplitude of 200 bar, and a temperature difference of 700 K. Such pressure swings and temperature differences are reasonable and achievable. These promising results are now being extended to include magnetohydrodynamic effects accurately. Once the proper design algorithm is in hand, we intend to begin construction of a complete engine.

Fig. 77. Schematic of a liquid-sodium acoustic engine one-half wavelength long. The velocity antinode at the center is in a magnetic field that enables the extraction of electrical power through magnetohydrodynamic effects. The stacks S_1 and S_2 serve the same function as in the gas acoustic cooling engine and are the second thermodynamic medium. Heat is extracted, perhaps, through tubular exchangers at $\dot{Q}_c$ and put in at $\dot{Q}_H$.

Magnetic Refrigeration

We are investigating theoretically and experimentally the concept of magnetic refrigeration, which exploits the magnetocaloric effect in solid paramagnetic and ferromagnetic materials to produce refrigeration from 4 K to 300 K. Magnetic materials can be made to execute the same thermodynamic cycles used in conventional gas refrigerators, but, in the case of the former, the cycle can be traversed, in practice, at nearly 100% efficiency. This contrasts to gas cycles, which suffer large losses at the compressor and expander stages. Hence, whereas the efficiency (independent of load and temperature) for gas machines ranges from less than 1% of Carnot efficiency for small loads to a maximum practical efficiency of 30 to 35% of Carnot for the largest loads, magnetic devices can be expected to operate at 65 to 70% of Carnot, independent of load and temperature. We expect magnetic devices to have the additional advantages of compactness, long life, reliability, and economy, but the disadvantage that a given magnetic working material can be used effectively over a temperature range of only $\sim \pm 30^\circ\text{C}$ about the Curie temperature T_C . Thus, to cover the range from 4 K to 300 K, several materials must be used in series.

A major thrust of our work is to uncover and characterize appropriate magnetic working materials. We have known for some time that ferromagnetic gadolinium metal ($T_C \sim 300$ K) and paramagnetic gadolinium gallium garnet, GGG ($T_C \sim 2$ K), are good refrigerants. In our search for others, we obtained high-quality samples of a dozen or so ferromagnetic gadolinium-based materials having T_C ranging between ~ 20 K and ~ 215 K. We made extensive calculations of the thermomagnetic properties of these materials using the Debye and mean-field models. Because the results of these calculations suggested that the intermetallic compound gadolinium nickel ($T_C \sim 70$ K) should be a particularly good refrigerant for the region from 40 K to 90 K, we conducted an extensive experimental program to measure such properties as magnetic susceptibility, specific heat, magnetization, adiabatic temperature changes (for fields up to 9 T), electrical conductivity, and thermal expansion coefficient—all over wide temperature ranges. These measurements confirmed our expectations for gadolinium nickel; now we are investigating methods of fabricating the compound for use in a device.

Our development of model refrigerators is divided into two classes, depending on the temperature range. Below ~ 20 K, paramagnetic materials are expected to give superior results, and in this range, little or no regeneration is required. Therefore a Carnot cycle can be used. Above ~ 20 K, the lattice heat capacity begins to dominate the magnetic thermal effects in paramagnets; at higher temperatures, ferromagnetic materials, for which these objections are not so severe, can serve well, but regeneration is required to achieve reasonable temperature spans so that such cycles as the Brayton or Ericsson must be used. We are designing and constructing both types of machines, which, because of the above considerations, require different approaches. Our low-temperature (4-K to 20-K) device is nearer completion.

A schematic diagram of our 4-K to 20-K refrigerator is shown in Fig. 78. In this Carnot-cycle design, nearly spherical granules of GGG are packed into screened rectangular compartments on the rim of a wheel, which rotates through the gap between a pair of superconducting solenoids wound on iron cores and supported by an iron yoke for flux return. As the wheel rotates inside a sealed housing, helium gas is pumped radially through ducts, located where the GGG reaches ~ 20 K as it is magnetized and where the GGG reaches ~ 4.2 K as it is demagnetized, and through external heat exchangers. Realistic calculations indicate this machine should develop 0.66 W of cooling power between 4.3 K and 15 K at an overall efficiency of 65% when operating at 0.2 Hz through a 6-T field.

Significant problems associated with all designs involve heat transfer and entrainment of fluid with the moving magnetic material. The latter problem is being solved by mechanical design. However, because establishing excellent heat transfer is crucial for obtaining high device efficiency and use of existing correlations (mainly on the basis of experiments with air near room temperature) is highly suspect for helium at low temperature, we began careful experimental studies of fluid helium flow and heat transfer through porous beds of magnetic materials. We intend to determine optimum conditions and bed geometries compatible with other refrigerator design criteria. Initial results clearly justify these efforts.

Fig. 78. Carnot-cycle wheel-type magnetic refrigerator, schematic drawing of device being tested.

Convection in $^3\text{He}/^4\text{He}$ Solutions

We have been studying nonlinear dynamics in thermally convecting dilute solutions of ^3He in superfluid ^4He from 0.7 K to 1.1 K. The novel elements of this hydrodynamic system include the low Prandtl number Pr of the solutions,* the ability to vary Pr by changing either the ^3He concentration or the temperature, the effective one-component fluid properties of the solutions, and the very low experimental noise level owing to the low temperatures and to cryogenic techniques. The nonlinear character of the convective state gives rise to a wide range of time-dependent phenomena, including the onset of oscillatory instability and the transition to deterministic chaos. We studied in detail the onset of oscillatory convection. At higher convective drive we also observed various theoretically predicted routes to chaos, including period-doubling cascades, incommensurate frequencies, and intermittency. For intermittent onset, we quantitatively characterized the transition as a function of both the convective drive and externally applied Gaussian noise. In understanding the complex nonlinear features of this system, we worked closely with theorists at the Los Alamos Center for Nonlinear Studies.

The onset of time-dependent motion is characterized by a single oscillation frequency, a temperature oscillation amplitude that increases linearly from zero as the convective drive ϵ is increased (see Fig. 79), and an onset drive that depends linearly on Pr . This transition from steady state to time-dependent convection is extremely sharp: the resolution in the oscillation amplitude is better than $0.5 \mu\text{K}$ and the resolution in ϵ is 0.01%. The oscillation frequency, which increases as $\epsilon^{1/2}$ from a finite value at the onset, is very stable and is measured to better than 0.01%.

We studied most quantitatively the intermittent transition to chaos. There are intervals when a stable, locked state exists. Interspersed with these intervals are chaotic bursts that increase in frequency as ϵ is increased beyond some threshold. We studied the effect of externally applied noise on the transition and measured the critical noise amplitude at which the intermittency is induced by the noise. From a time series we generate a power spectrum, which has in it both the periodic oscillations and the broadband noise. Figure 80 shows the onset of intermittent chaos as measured by the ratio of internal

* Pr is defined as the ratio of the diffusion coefficient for vorticity to that for heat.

Fig. 79. Temperature oscillation amplitude versus $\epsilon \equiv \Delta T / \Delta T_c - 1$, where ΔT_c is the critical value for the onset of steady convection ($\Delta T_c = 4.1$ mK at $T = 0.85$ K and a ^3He molar concentration of 1.5%).

noise power to total power for no applied external noise and for finite-amplitude applied noise. The onset occurs at lower drive for larger-amplitude applied noise. This feature is quantified in a critical noise “susceptibility,” which we find varies in an approximately linear fashion with the applied noise amplitude. Note that the entire transition occurs over a very small interval, 0.1%, in drive and that the fraction of the power associated with the chaotic broadband noise relative to that in the periodic motion is only about 1%. Other measurements that help characterize the transition are phase-space trajectories and Poincaré sections. We continue to study these chaotic phenomena and hope to quantitatively measure other transitions to chaos.

Tritium Beta Decay—Neutrino Mass Experiment

The initial major aim of our work is to produce an intense atomic beam of tritium that will constitute the source for the beta-spectrum determination associated with the neutrino-mass experiment conducted by Group P-3. Our first success was the attainment of $\text{H}_1/(\text{H}_1 + 2\text{H}_2)$ ratios $>95\%$ from our dissociator. However, this dissociation fraction (DF) must be maintained throughout a 4-m length of tube, the “Kleppner Bottle” (KB), that is the source region for the experiment. A major materials problem is presented by the walls of the KB. All metal walls catalyze recombination, dictating the use of dielectric materials. However, the KB must also be maintained at a potential of about -20 kV to reduce background. Buildup of charge on these dielectric walls during the experiment would cause changes in the potential and a distortion of the spectrum. We recently experimentally established an interesting solution to this problem. Measurements of the DF of hydrogen and deuterium beams emerging from the

Fig. 80. Ratio of noise power to total spectral power at the transition to intermittent chaos for different external noise amplitudes σ (in units of $\langle \delta T^2 \rangle^{1/2} / \Delta T_c \times 10^{-3}$). The onset temperature difference of intermittency for $\sigma = 0.0$, ΔT_c , is about 52 mK at an average temperature of 0.85 K and ^3He molar concentration of 1.5%.

ends of aluminum tubes cooled to 100 K show that $DF > 90\%$ can be maintained in such tubes. The dense uniform oxide formed on aluminum appears to have an extremely low probability (per bounce) of causing recombination of hydrogen isotopes near 75 K. The small thickness of the oxide would also result in a very large capacitance for charge and/or charge tunneling, which would imply acceptable voltage variations.

Our measurements of hydrogen and deuterium recombination in aluminum tubes as a function of temperature show a deep broad minimum near 120 K; the recombination probability per wall collision is $< 3 \times 10^{-5}$ for $100 \leq T \leq 135$ K. These results are similar to those previously observed for hydrogen recombination on Pyrex surfaces and are in qualitative agreement with theoretical predictions. Such low values for the recombination coefficient imply negligible recombination for atomic beam transport along tubes with an average number of wall collisions ~ 3000 , as planned in our tritium beta-decay experiment. These experiments will be repeated with tritium beams in the near future.

High-Pressure Physics of Simple Molecules

The development of the diamond-anvil cell (DAC) and ancillary techniques during the past decade opened a relatively simple, direct, economical, and very exciting route to the study of materials compressed into the megabar range. Such methods complement and extend our work with piston-cylinder devices (useful up to about 40 kbar for accurate equation-of-state determination). With DACs we can use a number of probes for characterizing the compressed material; most notable of these are x-ray diffraction and infrared and Raman spectroscopies. Our work uses these techniques to study the often remarkable and unexpected physical and chemical changes caused by pressurization of the condensed phases of simple molecules. A significant contribution of this program was the invention of methods for trapping samples of the gases and squeezing them to high densities (the largest linear dimension of a DAC sample is ~ 0.05 cm). In the following section, we briefly mention several typical recent experiments performed in this program. Some of the work was in collaboration with others from Groups M-6, WX-3, INC-4, and T-11.

Ammonia. The discovery of ammonia in planetary atmospheres prompted a new interest in NH_3 at very high pressures. We used a piston-cylinder apparatus to measure 1200 sets of pressure, volume, temperature, and sound-velocity data (P, V, T, and u) in fluid NH_3 from 195 K to 320 K at pressures up to 12 kbar. A Tait-type equation of state (EOS) with two quadratic parameters in T was fitted to the data with an rms deviation of only $\pm 0.2\%$ in V and $\pm 0.9\%$ in u, which is comparable to the experimental error. Our measurements of u, shown in Fig. 81, are the first to be reported for compressed NH_3 . They differ by up to 15% from values calculated from a National Bureau of Standards (NBS) 44-parameter EOS based on P-V-T data alone. Similarly, NBS values of the heat capacity at constant pressure C_p differ by as much as 30% from our derived values. We conclude that incorporating u in the formulation of an EOS markedly improves self-consistency of the results.

Xenon. According to theory, highly compressed xenon may undergo a phase change from fcc to bcc, triggering metallization at a pressure lower than the estimated value of 1.3 Mbar for fcc xenon. From x-ray diffraction photographs in a DAC, we found that xenon remains fcc up to at least 230 kbar. Atomic volumes are in good agreement with measurements at lower pressures and with zero-K calculations.

Nitrogen. We consider N_2 , a first-row closed-shell molecule, an ideal subject for study up to relatively high pressures and temperatures because its strong triple bond remains stable. From the characteristic Raman spectra measured in a DAC, we determined the phase diagram of N_2 up to 0.5 Mbar. As shown in Fig. 82, N_2 exists in at least four crystal forms: ordered cubic $\alpha\text{-N}_2$ (space group Pa3); disordered hexagonal $\beta\text{-N}_2$ (P6₃/mmc); ordered tetragonal $\gamma\text{-N}_2$ (P4₂/mnm); and disordered cubic $\delta\text{-N}_2$ ("Pm3n"). We use the characterization "Pm3n" because our spectral data show that there are extensive P-T regions where the lattice distorts from its earlier assigned space group Pm3n. At room temperature, the distortion appears to be continuous with pressure, whereas at low temperature, a discrete low-symmetry structure may be formed.

Fig. 81. Ultrasonic velocity of fluid NH_3 along various isobars. O, present measurement interpolated at even pressure; ●, measurement along vapor pressure (v.p.) curve, D. E. Bowen and J. C. Thompson, *J. Chem. Eng. Data* **13**, 206 (1968); —, calculated from present Tait EOS; dashed line, calculated from NBS EOS, L. Haar and J. S. Gallagher, *J. Phys. Chem. Ref. Data* **7**, 635 (1978); m.p., melting pressure curve from our earlier measurement.

Carbon Monoxide. Because CO is a close molecular analogue of N_2 , we carried out a parallel study on CO to see how subtle differences in the interaction potentials might affect the physics and chemistry of these molecules. At 300 K and 25 kbar, both solids crystallize into a disordered hcp structure with the molecules tipped from the c-axis (49° for CO and 54° for N_2). Compression to 40 kbar causes both solids to undergo a structure change to cubic Pm3n. In this form, N_2 is stable in the presence of green and blue radiation, but CO photoreacts. We have exciting evidence that a film-like polymer of CO forms in the DAC. The film can be removed at zero pressure, but it evaporates over a period of several hours.

Fig. 82. Phase diagram of condensed N_2 . Present spectral observations and characterizations from the present work: O, hexagonal $\beta\text{-N}_2$ (P_{63}/mmc); □, tetragonal $\gamma\text{-N}_2$ (P_{42}/mnm); Δ, "cubic" $\delta\text{-N}_2$ ("Pm3n"). Coincident points indicate coexisting phases. Solid lines incorporate earlier results made here and elsewhere.

Nitrogen Tetroxide. In support of the Laboratory's program on Fundamental Research on Explosives, we found from Raman spectroscopy in DACs that room-temperature N_2O_4 freezes at 4.6 kbar into cubic $\alpha\text{-N}_2\text{O}_4$, known at low temperature to have space group $\text{Im}\bar{3}$. Laser irradiation of $\alpha\text{-N}_2\text{O}_4$ causes the formation of a new form, $\beta\text{-N}_2\text{O}_4$, the structure of which has not been completely identified but is known to be noncubic with N-N bond axes aligned. At pressures from 15 to 30 kbar, $\beta\text{-N}_2\text{O}_4$ transforms reversibly into an ionic form, NO^+NO_3^- , in contrast to $\alpha\text{-N}_2\text{O}_4$, which is stable up to at least 76 kbar.

Theory. As theoretical guidance for the high-pressure program, a Gordon-Kim (GK) electron-gas model was used to study the compressibility and structure changes of N_2 , CO_2 , C_2H_2 , and CO at high pressure. The computed P-V curves are in close agreement with measurements, but the predicted transition pressures show large deviations from experiment. A variant of the GK model, which gives good results for rare-gas interatomic potentials, was extended to molecular crystals. We also developed a new, time-saving method for studying effects of crystal environment on the ground- and excited-electronic states of solid argon and xenon, with modifications for molecular systems.

High-Pressure Solid-State Physics

For many years, temperature and magnetic field were prime variables in the study of solid-state physics phenomena. More recently, the dimension added by external pressure variations is appreciated as being extremely interesting and valuable in understanding effects arising from both short- and long-range interactions in solids. Our work in this area was a leading factor in the development of new techniques as well as in the discovery of new phenomena. Some recent results are mentioned below.

Electrical Conductivity in Polyacetylene. When polyacetylene $(\text{C}_2\text{H}_2)_x$ is compressed, a preferential shortening of the weak interchain bonds results in a substantial change in the electronic density of states. A group measuring optical absorption spectra at the University of Pennsylvania recently found that application of 13 kbar caused the Peierls energy gap E_g in $(\text{C}_2\text{H}_2)_x$ to decrease from 1.39 to 1.22 eV. If this large red shift were to continue with pressure, then gap closure and electrical conductance might occur in the region from 100 to 200 kbar. We measured the infrared absorption spectrum of $(\text{C}_2\text{H}_2)_x$ compressed hydrostatically up to 134 kbar with room temperature helium in a DAC. At 55 kbar, the band gap narrowed to about 0.8 eV. Above this pressure, however, the absorption edge was too poorly defined to measure. Between 55 and 134 kbar the sample darkened and eventually turned yellow. From the work so far, we conclude that polyacetylene under pressure undergoes chemical changes before it becomes a conductor.

Ferromagnetic Spin Fluctuations in Some Actinide Compounds. A signature of spin fluctuations is a high-temperature Curie-Weiss susceptibility that indicates localized 5f electrons and evolves to a temperature-independent, enhanced-paramagnetic susceptibility as the temperature is lowered below a characteristic value called the spin-fluctuation temperature T_{SF} . Below T_{SF} , the spin susceptibility arises from a strongly correlated set of itinerant or band-like electrons. In addition to the susceptibility change, theory predicts that for $T \ll T_{\text{SF}}$ the low-temperature heat capacity should be proportional to T^3 in T/T_{SF} and the resistance should scale as $(T/T_{\text{SF}})^n$, where $n = 2$ or $3/2$ depending on sample purity. Only two materials, UAl_2 and UPt_3 , are known to exhibit all of these features. The latter is of special interest because recently it was discovered to exhibit "heavy fermion" superconductivity, where the mass of the electrons responsible for the superconductivity is several orders of magnitude greater than the free-electron mass. Investigations of these prototypical materials as a function of pressure are important to clarify the mechanisms responsible for these interesting phenomena and to improve our understanding of the electronic properties of actinides under extreme conditions.

In our collaborative efforts with others in Group MST-5 and at the University of California, San Diego, we measured the resistance of polycrystalline UAl_2 and single crystal UPt_3 as functions of temperature from 1.0 K to 290 K and of hydrostatic pressure up to 17 kbar. For $T < 20$ K, the resistance of both samples is proportional to $[T/T^*(P)]^{3/2}$, where $T^*(P)$ is a pressure-dependent fitting parameter.

In the spirit of theoretical models, we chose $T^*(P=0)$ to be equal to $T_{SF}(P=0)$ obtained (by others) from heat capacity and susceptibility measurements. With this assumption, we deduced $T_{SF}(P)$ from the low-temperature resistance measured at various fixed pressures. Figure 83 shows T_{SF} versus P for UAl_2 and for UPt_3 measured along both the hexagonal c-axis and in the a-b plane. We conclude from these results that pressure suppresses spin fluctuations, or, alternatively, that pressure broadens the uranium 5f level near the Fermi energy. The relatively large anisotropy in the spin-fluctuation behavior of UPt_3 might be expected because of its noncubic crystal symmetry.

We also discovered rather remarkable scaling of the resistance over an extended temperature interval. Applying the current spin-fluctuation model prediction that $R = f(T/T_{SF})$ for $T \ll T_{SF}$, we find that scaling continues up to at least room temperature for UAl_2 and up to about 100 K for UPt_3 . Results for UAl_2 are shown in Fig. 84. Why scaling persists over such a large temperature range and why the scaling regime differs by a factor of 3 in apparently similar materials remain questions for theorists to answer.

Fig. 83. Spin-fluctuation temperature T_{SF} as a function of hydrostatic pressure for polycrystalline UAl_2 and for single-crystal UPt_3 measured along the c-axis and in a plane orthogonal to the c-axis.

Fig. 84. Scaling of the measured electrical resistance of UAl_2 according to the ratio of T/T_{SF} , where T_{SF} is the spin-fluctuation temperature, for pressures up to 17.5 kbar. The inset shows the unscaled resistance-vs-temperature data at several constant pressures.

Pressure-Induced Superconductivity. In recent years, attempts to characterize the general phenomenon of superconductivity stimulated experiments involving new or novel materials as well as extended values of such external parameters as magnetic field and pressure. The results were sometimes surprising and revealed significant details of the competition at the ground state, especially between superconductivity and various types of magnetic ordering and between superconductivity and charge-density or spin waves. We have been actively engaged in this type of work, concentrating on how externally applied pressure mediates different types of competition. Our experimental discoveries of pressure-induced superconductivity in such diverse materials as $\text{Eu}_{1.2}\text{Mo}_6\text{S}_8$ and ditetramethyl-tetraselenafulvalene fluosulfite, $(\text{TMTSF})_2\text{FSO}_3$, illustrate these efforts.

In both compounds, superconductivity is absent at ambient pressure but appears after the application of moderate pressure. This behavior is ascribed, in both cases, to a low-temperature structural distortion that under ordinary conditions introduces a gap over all or a part of the Fermi surface, that is, a large number of potential BCS states necessary for superconductivity are not available, so superconductivity is suppressed; the role of pressure is to suppress the structural distortion, which then makes the BCS states more available.

For $\text{Eu}_{1.2}\text{Mo}_6\text{S}_8$, details of the pressure dependence of both the structural and superconducting transitions were explained quite quantitatively on the basis of a competition between superconductivity and a charge-density wave-type state. The anomalous behavior of the superconducting critical magnetic field H_C as a function of pressure and temperature is shown in Fig. 85. Note that the superconducting state is most greatly enhanced at $P \approx 14$ kbar, with a zero-field transition temperature of 11 K, and is suppressed at both higher and lower pressures.

In the case of $(\text{TMTSF})_2\text{FSO}_3$, an anion ordering, giving rise to a metal-insulator transition, is responsible for suppressing superconductivity. Figure 86 shows the complexities of the P-T phase diagram for this material, which indicates the presence of an intermediate glassy state and the onset of superconductivity near 2 K for $P > 5$ kbar.

The above results were obtained through a comprehensive program, measuring such properties as heat capacity, Hall coefficient, resistivity, thermoelectric power, and structure (using x-ray diffraction from ordinary and synchrotron sources) as functions of temperature and pressure. The work was performed in collaboration with others from the US Naval Research Laboratory, Bell Laboratories, and the University of California at Los Angeles and San Diego.

Fig. 85. The critical field H_{C2} of $\text{Eu}_{1.2}\text{Mo}_6\text{S}_8$ vs temperature at various values of pressure. The lines are drawn to aid the reader.

Fig. 86. Temperature-pressure phase diagram for $(\text{TMTSF})_2\text{FSO}_3$.

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