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Physics Division Progress Report

January 1, 1993–December 31, 1993

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Los Alamos
NATIONAL LABORATORY

Los Alamos, New Mexico 87545

MASTER

PHYSICS DIVISION PROGRESS REPORT

January 1, 1993–December 31, 1993

ABSTRACT

This report provides selected accounts of significant progress in research and development achieved by Physics Division personnel during the period January 1, 1993, through December 31, 1993.

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Mission and Goals

The mission of the Physics Division is to further our understanding of the physical world, to generate new technology in experimental physics, and to establish a physics foundation for current and future Los Alamos programs.

The goals of the Physics Division are to

- provide the fundamental physics understanding supporting Laboratory programs;
- investigate the basic properties of nuclear interactions, high energy-density systems, and biological systems with a view toward identifying technologies applicable to new Laboratory directions;
- identify and pursue new areas of physics research, especially those to which the unique capabilities of the Laboratory may be applied;
- explore interdisciplinary areas of scientific endeavor to which physical principles and the methods of experimental physics can make an important contribution; and
- maintain strength in those disciplines that support the Laboratory mission.

The Physics Division pursues its goals by

- establishing and maintaining a scientific environment that promotes creativity, innovation, and technical excellence;
- undertaking research at the forefront of physics with emphasis on long-term goals, high risks, and multidisciplinary approaches;
- fostering dialogue within the Division and the scientific community to realize the synergistic benefits of our diverse research interests;
- encouraging the professional development of each member within the Division; and
- conducting all of its activities in a manner that maintains a safe and healthful workplace and protects the public and the natural environment.

The current organization of the Physics Division is illustrated in Fig. I-1. Details of the Division's staff and funding levels for fiscal year 1993 are presented in Appendix A. Publications, presentations, and patents are listed in Appendix B.

Group Descriptions

P-1: High Energy-Density Physics

Kurt F. Schoenberg, Group Leader

The mission of Group P-1 is to apply our knowledge of plasma physics, atomic physics, pulsed-power technology, and laboratory-based experiments to study the physics of matter in a high energy-density state. We use our understanding of high energy-density matter to address problems of national significance in nuclear weapons, conventional defense, magnetic fusion energy, and industrial competitiveness.

As part of the AGEX II (AboveGround EXperiments) Program, we are studying the physics of electromagnetically driven implosions and plasma-flow-switch technology and the interaction of ultrahigh irradiance lasers with matter to provide laboratory facilities that will help maintain the nations nuclear-weapons competency and stockpile stewardship. In theater missile defense, we are analyzing the physical limitations of hypervelocity atmospheric flight with a view toward boost-phase missile interception. As part of the National Magnetic Fusion Program, we are making measurements of fusion products on existing tokamaks, developing diagnostic techniques for the next-generation tokamaks, and launching a new program to understand and hopefully mitigate the effects of plasma disruptions in large magnetically confined systems. We are helping to make United States industry more competitive by applying our knowledge of plasma physics to do surface modification of materials. These techniques will enable the treatment of large areas with a variety of materials in a way that is economical and will not require the use of environmentally damaging chemicals.

P-1 investigates a wide variety of experimental-plasma and atomic-physics problems, ranging from basic research to applied science for the development of new technologies and applications. The group was founded in 1979 to exploit new developments in laser and pulsed-power technology for applications to physics problems relevant to the nuclear-weapons program. Today the group conducts research relevant to nuclear-weapons physics, fusion, space exploration, conventional defense, industrial competitiveness, and basic research. Originally named the New Initiatives Group, P-1 still retains much of the flavor of the initial group in that it pursues projects that are conceptually new and usually of a high-risk nature.

Group members are studying the interaction of very intense, subpicosecond laser pulses with matter. At intensities achievable on the LABS II (Los Alamos Bright Source II) laser, electric fields within the laser focal spot may exceed $500 \text{ V}/\text{\AA}$. These laser intensities, which exceed $5 \times 10^{18} \text{ W}/\text{cm}^2$, produce extreme states of matter for a number of important high energy-density experiments. Our present experiments are aimed at producing an intense x-ray source to gain an understanding of the extreme nonequilibrium plasmas that produce this x-ray emission. We are investigating x-ray emission mechanisms, including emission from highly stripped high-Z ions, harmonic conversion, x-ray production from solid targets, and the development of an intense x-ray flashlamp. Our highly efficient conversion of laser energy into x-ray line emission of ultrashort duration ($< 5 \text{ ps}$) led to the production of the brightest keV x-ray source ($10^{14} \text{ W}/\text{cm}^2$) yet produced in the laboratory. Such sources can be used to pump a laboratory x-ray laser, to generate unusually strong shocks ($> 1 \text{ Gb}$), and to study radiation processes relevant to nuclear weapons.

P-1 uses high-current, pulsed-power sources, such as the 4.3-MJ Pegasus capacitor bank and explosive pulsed-power facilities, to produce high-energy imploding plasmas. These sources can generate electrical

currents exceeding 10^7 A, which create implosions that are rich in hydrodynamic physics and produce intense bursts of x-rays that may ultimately be used for weapons-physics and dense-plasma-physics studies. Our present Pegasus experiments have produced 80-kJ, 100-ns bursts of x-rays; an extensive array of diagnostics has been used to characterize both the x-ray emissions and the imploded plasmas that produced them. We are also developing a fast, high-current opening switch to amplify the Pegasus electric power by a factor of about 10. With this switch, called the plasma flow switch, we have demonstrated such amplification factors into nonimploding loads. The success of experiments planned this year to drive imploding loads with the plasma flow switch will be a critical milestone toward generating x-ray bursts in the 1- to 10-MJ range using advanced capacitor banks or explosive generators.

Another project, aimed at understanding the properties of hot, dense plasmas, uses a hot-plasma discharge through a thin aluminum wire imbedded in glass. The goal is to produce a well-characterized, homogeneous, dense plasma and to make accurate transport and equation-of-state (EOS) measurements in a system in which plasma ions are strongly coupled (i.e., the Coulomb potential energy between ions exceeds the thermal energy of each ion). These measurements are now testing new theories of dense plasmas and will provide a valuable data base for many high energy-density applications. Experiments this year have produced near-solid-density aluminum plasmas at temperatures above 20 eV. We now have the diagnostics in place to measure plasma temperature, pressure, density, and electrical resistivity. Preliminary measurements of EOS and resistivity are already characterizing the strongly coupled plasma contributions to these quantities.

P-1 contributes to the National Magnetic Fusion Program through the development of diagnostics for present and future tokamaks. The two components of this effort are in fusion-product diagnostics and the development of an intense diagnostic neutral beam. Our fusion-product diagnostic work focuses on burning plasmas with a view toward future large tokamaks where present designs for charged-particle detectors are insufficiently hardened to radiation and high temperature. New detectors based upon Faraday cups or preradiation-damaged, solid-state detectors are being evaluated. We are also examining techniques to improve the spatial imaging of neutron emission and new designs for the spectroscopic measurement of gamma rays produced through fusion processes.

The group is collaborating in ongoing fusion-product research at the Tokamak Fusion Test Reactor (TFTR) at Princeton University to measure alpha-particle pressures using neutron-activation techniques and to develop improved detectors for measuring so-called "lost" charged-fusion products. We are developing a prototype of an intense-neutral-beam source that will be used as a diagnostic probe on tokamaks to determine thermalized alpha-particle distributions and ion temperatures.

In the control room, James C. "Bucky" Cochrane of Group P-1 verifies that all experimenters are ready just before firing Pegasus II.

FN93-209-018

A high beam intensity will be required for experiments involving large burning plasmas. These experiments are planned for the International Thermonuclear Experimental Reactor where presently spectroscopic techniques, which use low-intensity, long-pulse neutral beams, cannot produce the required signal. Our intense-neutral-beam source will accelerate protons or deuterons using high-power, ion-diode technology and gas-cell neutralization techniques.

P-1 is involved in the national physics design of the proposed successor to the TFTR, the Tokamak Physics Experiment (TPX). As members of the TPX project physics team, P-1 staff are helping to evaluate diagnostic strategies for the TPX, the construction of which will begin in several years. We have begun a new project this year to investigate a novel application to produce dense-plasma confinement in a Penning trap. This project, a joint effort between P-1 and T-15, will hopefully demonstrate that the local density in a Penning trap can exceed the Brillouin limit and that we can use this effect to produce a significant number of fusion reactions.

Our understanding of large, coaxial plasma accelerators allowed us to contribute to the development of electric thrusters for space exploration. Electric propulsion offers the advantage of high exhaust velocity (or specific impulse), which may enable future space missions such as solar-electric orbit transfer or the robotic exploration of the outer planets. Through experiments at our Coaxial Thruster Experiment (CTX) Facility, we are investigating the properties of these coaxial plasma accelerators to infer the balance between radiative losses, electrode losses, axially directed kinetic energy, mass flow, and thruster efficiency. An experimental understanding of these phenomena, coupled with the modeling being done by T-15 and NIS-1 (formerly SST-7), is essential before the scaling of electric thrusters to mission dimension can be evaluated.

P-1 is working with United States industry to develop new applications for plasmas in material processing. Three plasma-processing techniques are being studied in our laboratories. An intense ion-beam

source has been developed at our Anaconda accelerator to produce large-area dense plasmas that can be used to modify the surface of materials and to synthesize advanced materials. This technique offers several significant advantages over conventional techniques. The first experiments, started at the end of 1991, were designed to study the congruent deposition of complex stoichiometric thin films. We have now successfully produced large-area samples of 1-2-3 high-temperature superconductors and diamond-like carbon thin films. The second plasma-processing technique, plasma-source ion implantation (PSII), uses a high-current power source to implant ions at energies above 50 keV. Modifying surfaces by the PSII method can potentially improve the hardness of materials and make them essentially abrasion and corrosion resistant. The

The Los Alamos PSII Facility is the largest of its kind in the world.

PSII technique may reduce processing costs significantly as compared with conventional line-of-sight ion beam techniques. Our CTX Facility is being configured to test the PSII technique at unprecedented high currents and sample sizes. To facilitate the development of PSII, we have established a Cooperative Research and Development Agreement with universities and industry where applications of PSII may be of significant economic benefit. In another project, we are using a technique called plasma-immersion ion implantation (PIII) to make thin film transistors for flat panel displays. If successful, the PIII technique could produce substantial reduction in cost and increase the reliability of large-area flat panel displays.

P-1 is investigating the physics of hypervelocity missile interceptors for theater ballistic missiles (TBM). Hypervelocity interceptors address the emerging need to interdict hostile TBMs before the release of submunitioned warheads. Of central importance to hypervelocity missile design is understanding missile performance in the operational regimes of interest. In 1993, P-1 led an assessment of hypervelocity interceptor performance for the Ballistic Missile Defense Organization. This assessment included the design of a series of flight experiments to measure and assess the environmental phenomenology of hypervelocity flight, including the properties and effects of shock-driven plasma generation. This assessment serves as an important point of reference for the future United States development of hypervelocity interceptor systems.

Group P-2 conducts a broadly based research program in nuclear and particle physics that addresses issues of current interest in nuclear structure, the nuclear EOS, and quantum chromodynamics. Current projects include approved and ongoing experiments at the Fermi National Accelerator Laboratory, the European laboratory for particle physics (CERN), Brookhaven National Laboratory, and the Los Alamos Meson Physics Facility (LAMPF). The group also pursues a vigorous research and development program in detector technology. The group's expertise acquired in this field is applied to programmatic support for neutral-particle-beam (NPB) efforts in strategic defense.

A wide variety of experiments are presently under way. In the recently completed experiment E772 at the Fermi National Accelerator Laboratory, group members have measured the nuclear target dependence of lepton-pair production from photon beams to understand how the quark and gluon structure in nuclei differs from that of free nucleons. A high-speed, parallel-processing computer was constructed and operated at Los Alamos for a timely analysis of the data. The first measurement of the antiquark sea and its target dependence shows no enhancement over what is observed for ^2H targets. This result contradicts most current theoretical models on that subject. In experiment E789 at the Fermi National Accelerator Laboratory, group members are searching for two-body decays of mesons and baryons containing bottom quarks to elucidate the relevant details of quantum chromodynamics. A major upgrade consisting of more than 10,000 channels of solid-state, silicon-strip detectors has been added to the experiment E772 detector for that purpose. The first data were collected in 1990, and a major data-taking run was begun in 1991.

Group members are exploring the field of relativistic heavy-ion physics. In their search for the formation of a quark-gluon plasma, Group P-2 made some of the first measurements of transverse energy flow and particle production (with the highest-energy beams available in

P-2: Medium-Energy Physics

Wayne W. Kinnison, Group Leader

the world). Group members will make even more detailed measurements of inclusive particle production and two-particle correlations to improve our understanding of the space/time evolution of these reactions. For that effort, the design and construction of an entirely new spectrometer has been completed at CERN (NA44); the first data from that experiment were reported in 1991. The members of the relativistic-heavy-ion group are also playing a lead role in the proposed PHENIX experiment, which is to be part of the Relativistic Heavy Ion Collider Program at Brookhaven National Laboratory.

In other experiments, group members have recently completed a search for rare (forbidden) kaon decays, which, if they exist, would have profound implications for the Standard Model. The results from experiment E791 at Brookhaven National Laboratory have set the most stringent upper limits on these decays.

Los Alamos is a member of the L3 experiment at the CERN Large Electron-Positron Collider. Members of P-2 are involved in the current running of the L3 experiment and have taken a lead role in upgrading that detector. Other members of P-2 were involved in the Gammas, Electrons, and Muons (GEM) experiment proposal for the Superconducting Super Collider (SSC). In a related effort, a major research and development program to develop a silicon-tracking subsystem for research at the SSC was initiated by another collaboration working on the Solenoidal Detector Collaboration experiment for the SSC. Groups P-2 and MEE-12 (now ESA-8) were responsible for the mechanical and cooling design work for the entire silicon-tracking structure. The goal of all of these activities was for Los Alamos to play a major role in the SSC physics program.

Group P-2 is currently carrying out a number of programmatic efforts involving the development of detectors. A project involving the sensing and imaging of an NPB has successfully characterized the quality of NPBs at Argonne National Laboratory. This experience is being used for the construction of a larger system at Los Alamos.

P-3: Subatomic Research and Applications John D. Moses, Group Leader

Tom Burritt and Mel Anaya complete the final adjustments on a neutrino source manipulator before its shipment to the SAGE experiment in Russia. The apparatus will be used to position a ^{51}Cr neutrino source in a test of extraction efficiency of ^{71}Ge atoms created in gallium by the $^{71}\text{Ga} + \nu$ inverse beta-decay reaction.

P-3 is an experimental physics group engaged in research projects in several areas of basic and applied physics. The group is active in the study of the weak interaction, in the use of lidar (Light Detection And Ranging) technology for remote sensing, and in the AGEX Program. We believe that part of our mission is to maintain a strong and flexible experimental program, thus P-3 scientists are involved in a number of small research efforts. We are active in the development of adaptive hardware for event recognition and instrument control and in the development and study of autonomous robots. We are building a sensitive torsion balance to measure the Newtonian gravitational constant and to investigate new techniques to study non-Newtonian aspects of gravity, and we are participating in a study of cryptographic-key transmission using quantum coherence to guarantee security.

The weak-interactions group in P-3 is active in several experiments in neutrino physics. We are participants in SAGE, the Russian American Gallium Experiment, a collaboration with a large research group in Russia to measure the low-energy solar-neutrino flux using a radiochemical gallium detector. This measurement is sensitive to low-energy neutrinos generated by proton-proton fusion in the sun; this part of the solar-neutrino flux is directly related to solar luminosity and thus is relatively insensitive to the solar model. Results to date indicate that the flux is at the lower limit of the predictions of solar models and suggest that particle physics may be responsible for the solar-neutrino anomaly.

P-3's weak-interactions group is also part of the Sudbury Neutrino Observatory (SNO) collaboration, a Canadian, American, and British project to build and operate a neutrino observatory based on a 1,000-tonne heavy-water detector that will be capable of distinguishing between astrophysics and particle-physics solutions to the solar-neutrino problem. SNO is now being constructed in a nickel mine in Sudbury, Canada. P-3 is responsible for acquiring phototubes, for overseeing the construction of the acrylic vessel to hold the heavy water, for developing detectors of weak neutral-current neutrino interactions, and for developing the data-acquisition system.

The weak-interactions group is also looking for violations of time-reversal symmetry in the beta decay of the neutron by precisely measuring the triple correlation coefficient with polarized neutrons from the National Institute of Standards and Technology reactor and a novel detector.

P-3 is active in several areas of AGEX in the nuclear-weapons-program arena. We are developing and building small Marx banks for various pulsed-power applications, including radiographic techniques for diagnostic applications on the Pegasus II Facility, and we are providing calculational support to Pegasus II experiments. We are developing a novel interferometer using laser light modulated at microwave frequencies and carried by optical fibers to study shock propagation and high-explosive burn, and we have an active experiment studying the properties of sonoluminescence in water-filled glass bulbs.

In collaboration with others in the Laboratory, P-3 is active in the use of lidar technology in various projects involving remote sensing in the atmosphere. Lidar uses range-resolved backscattered laser light to detect atmospheric chemicals and particulates. The collaboration has developed truck-mounted, man-portable, airborne and shipborne lidar systems. Among other applications, we used these systems to measure the spatial and temporal water-vapor concentration and water flux above irrigated fields and over the tropical ocean. We also carried out extensive measurements of atmospheric aerosols as part of various clean-air initiatives, investigated the use of an elastic backscatter lidar to detect and track rocket plumes, and worked toward the design of satellite-based systems.

We have begun a research project into the development and behavior of autonomous robots, which are based on simple, processorless devices primarily designed to survive in hostile environments. These devices are based on smart mechanics and simple electronic-control structures. They mimic the functionality of biological organisms from simple plankton-like invertebrates to members of the insect and crab family. The hope is that robots can be designed to survive various types of environments and then can be "domesticated" to do useful work.

P-3 is involved in a project with groups in NIS Division to develop tools for fast and smart adaptive signal-recognition techniques using

Photo by Peter Doe

This 15-ft-high, 18-ft-wide test portion of the SNO heavy-water containment sphere represents only 6% of the total area of the final spherical vessel that will be placed at a depth of 6,800 ft in the INCO Creighton mine in Sudbury, Canada. The test portion was built to demonstrate the construction principles behind the final sphere.

Photo by Ed Robinson

Gabe Luther of Group P-3 examines the apparatus used to measure the strength of the gravitational force.

digital signal-processing chips, adaptive fuzzy-logic systems, neural-net-based hardware, and field-programmable gate arrays. The use of this technology will enable the development of combined hardware and software, which is adaptable to changing signal-acquisition conditions and sensor environments in real time and is able to handle decision-making problems when confronted with conflicting information from several different types of sensors. P-3 is building a fuzzy-logic comparator board for evaluation and testing and is developing an on-board event classifier for the FORTE (fast on-orbit recording of transient events) small-satellite project.

Photo by Ed Robinson

The water-filled sonoluminescent flask used to determine the temperature and duration of sonoluminescent light pulses is shown with the seven sonic transducers.

P-4: Laser-Matter Interaction and Fusion Physics

Joseph M. Mack, Group Leader

Group P-4 is responsible for planning and executing laser-target interaction experiments covering a wide spectrum of interests, including laser fusion and fundamental laser-matter interactions.

The group's primary mandate is to understand the physics of laser-target interactions through experiments performed at appropriate world-class facilities such as Nova (Lawrence Livermore National Laboratory), Trident (Los Alamos), Omega (University of Rochester), and Helen (Atomic Weapons Establishment, United Kingdom). Such experiments address physics issues associated with inertial confinement fusion (ICF) and other important aspects of laser-matter interactions. Our scientific interests involve using the LABS to investigate fundamental laser-matter interactions at extremely high laser intensities.

Our magnetic-fusion effort is providing data-acquisition physics expertise for the reversed-field pinch facility in Padova, Italy. Other activities include data analysis and archiving of the results of the now dismantled Los Alamos ZT-40M reversed-field pinch.

P-6: Biophysics

Charles C. Wood, Group Leader

The mission of Group P-6 is to apply physics knowledge and techniques to an increased understanding of important biological phenomena and, in turn, to use biological phenomena to elucidate physical principles of complex systems. Group members are engaged in biophysical research over a wide range of physical scales: ultrasensitive detection and characterization of individual molecules using laser fluorescence; the molecular basis of signal transduction in retinal photoreceptors; biophysical changes in red blood cells in aging and their implications for blood storage and transfusion; characterization of the structure and dynamics of protein molecules and their implications for protein function; development, validation, and application of noninvasive techniques for measurement of human brain function; and development of three-dimensional computational models of the human brain.

Group P-6 was founded in 1988 with the goal of exploiting the scientific and technical resources of the Physics Division in the biosciences. The group has strengthened existing biological projects within the Division and initiated new bioscience efforts in a number of directions.

Members of P-6 and their collaborators have extended their recent accomplishment of a long-sought goal of researchers in ultrasensitive detection—the detection of single molecules in a liquid. The goal of the detection research is to measure and characterize the spectroscopic properties of individual molecules. Such spectroscopic measurements can be used to identify the presence of a particular molecular species in an extremely dilute solution, or they can be used to probe the local environment that surrounds an individual molecule. The former capability promises a new level of speed and sensitivity for medical diagnostics, whereas the latter capability makes it possible to study properties of biological systems that cannot be measured when lack of sensitivity confines measurements to the determination of the average properties of a large ensemble of microenvironments. Thus far, the spectroscopic properties measured at the single-molecule level include emission spectra, fluorescence lifetime, and total emission intensity. We are exploring applications of the new technology both for basic research and for medical diagnostics.

P-6 work on retinal phototransduction stems from the observation that the visual pigment rhodopsin, shared by man and all other vertebrates, is linked to the photoreceptor ion channels via a G-protein (transducin), which modulates the rod enzyme cyclic-GMP phosphodiesterase. G-proteins are guanine-nucleotide binding proteins that link cellular-signal receptors to amplifying-effector systems and thus participate in the flow of information across the cell membrane. The G-proteins serve in many cell types as a locus for the function of an activated receptor that modulates nucleotide binding to the G-protein and thereby modulates its function. Many neuronal and hormonal signals are dependent upon the participation of G-nucleotide binding proteins; they can amplify, modulate, and communicate signals. There is evidence that a single, activated rod photon receptor (rhodopsin) can in turn activate more than 30,000 G-proteins within a very short time period. This is the molecular basis of single-photon sensitivity. P-6 is studying two aspects of G-protein-dependent, photon-based signal processing. The first relates to evidence for cooperation between the G-protein and the active photon receptor, rhodopsin. The binding of the first G-protein to rhodopsin facilitates the binding of the second by 2 orders of magnitude. This positive cooperativity appears to be essential for the highly sensitive, yet noise-free, operation of biological photon transducers. Group members are also studying the role of rod protein phosphorylation in regulating rod sensitivity, and especially signal amplification, in the dark adapted state.

P-6 studies of mammalian erythrocytes (red blood cells) are based on biophysical relationships between the ratio of red-cell-membrane area to cytosolic volume. This ratio and the intrinsic physical properties of red-cell membranes reliably predict whether or not erythrocytes can traverse small capillary channels. Refrigeration degrades red-cell-membrane area principally by peroxidative pathways that culminate in the extrusion of vesiculated lipid. Refrigeration also attacks the sodium transport apparatus via peroxidative pathways and, to a lesser extent, via biochemical modifications of the gain control on the sodium pump. The biochemical and biophysical basis of refrigeration-induced damage has been characterized and effective countermeasures have been identified. Current work focuses on the optimization of protective measures and empirical testing of their efficacy by measuring erythrocyte survival in the transfusion recipient. The conceptual and mechanistic homology between red-cell senescence *in vivo* and refrigeration-induced damage is also an area of study. Finally, dramatic individual differences in red-cell

biophysical properties and Na⁺ pump activities have been observed among genetically diverse populations of humans. The potential clinical significance of these differences is being investigated.

The goals of P-6 studies of protein dynamics are to describe protein motion in atomic detail and to understand the consequences of protein dynamics for protein function. Our approach is to bring crystals of the CO complex of the protein myoglobin down to liquid-helium temperatures in a cryostat, photolyze the CO with a flash of light, and observe the subsequent rebinding reaction with x-ray Laue crystallography. We have constructed and tested a low-temperature Laue camera, determined the freezing conditions for the CO crystal needed to maintain the high degree of order required for Laue diffraction, and analyzed diffraction patterns obtained at 5 K. Our results show that under the right conditions protein crystals can be frozen and still produce high-resolution (better than 1.9 Å) Laue diffraction data.

The P-6 neuroscience effort focuses on the use of magnetoencephalography (MEG) and magnetic resonance images (MRI) to develop a means of noninvasive imaging of the human brain that combines structural and functional information at high spatial and temporal resolution. MEG involves the use of Superconducting QUantum Interference Devices (SQUIDS) to measure magnetic fields associated with human brain activity. The magnetic fields of the brain (which are approximately a billion times smaller than that of the Earth) require sensitive magnetic sensors, magnetic shielding from the environment (currently implemented as a shielded room), and advanced signal-enhancement and modeling techniques. Because magnetic fields readily penetrate the skull, MEG offers the potential for noninvasive measurement of brain *function* in much the same way that computed tomography and MRI allow the noninvasive measurement of brain *structure*. MEG has therefore generated considerable promise as a tool in basic neuroscience for functional mapping of the human brain, as a

clinical tool for the assessment of neurological and psychiatric disorders, and as a possible signal for use in the development of neural prosthetics and human-machine interfaces and in other applied contexts. Group members are engaged in projects to design improved multichannel magnetic sensors, to develop more accurate mathematical models for the electrical and magnetic signals from the brain, to validate MEG using known current sources in computational and physical models of the brain, and to use MEG to address important questions in basic neuroscience and in research on neurological and psychiatric disorders. Many of these projects are conducted in collaboration with the VA/LANL/UNM Center for MEG, a consortium that includes Los Alamos, the University of New Mexico, and the Albuquerque Veterans Administration Medical Center and is sponsored by the United States Department of Veterans Affairs. In addition to MEG and anatomical MRI, a rapidly expanding number of techniques such as positron-

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Bill Overton (right) and Ed Flynn examine the configuration of superconducting imaging sensors, which were designed to test Group P-6's new method of measuring weak magnetic fields from the human brain. The plates, which contain the SQUIDS (the small device being inserted into a groove), represent the imaging surface. They become superconducting when immersed in a dewar of liquid helium.

emission tomography, functional magnetic resonance imaging, and single-photon-emission computed tomography allow brain structure and function to be characterized over a wide variety of scales. The P-6 Brain Mapping Project is part of a nationwide effort to develop three-dimensional computational models of the brain in which a variety of structural and functional information can be represented for storage, retrieval, and analysis.

Fundamental research on condensed matter is the primary focus of Group P-10 (now MST-10). The spectrum of materials studied ranges from liquids and superfluids to solids exhibiting novel magnetic, superconducting, and nonlinear properties. Investigations are carried out from ambient to extreme conditions of very low temperatures, very high pressures, and magnetic fields. P-10 capabilities complement those represented in the Laboratory's newly formed Materials Division (MST) of which P-10 has become a part.

Historically, P-10 has been known as the cryogenics group because of its focus on expertise in low-temperature research. Although most of the group's research retains cryogenic aspects, the scope has broadened to include a wider variety of research topics in condensed-matter and thermal physics. One basic-research component in P-10 concentrates on the discovery and characterization of novel materials, particularly those having strong electron-electron correlations. This general class of materials includes high-temperature superconductors, heavy-electron systems, compounds based on C_{60} molecules, and materials showing valence fluctuations and metal-insulator behavior. The physics of these materials is studied using a broad range of techniques that probe macroscopic and microscopic magnetic, electronic, structural, and phononic properties. Materials are characterized macroscopically through

- low-temperature specific heat,
- temperature-dependent electrical resistance at ambient and high pressures,
- magnetoresistance and Hall coefficient measurements to 11 T,
- thermoelectric power,
- static magnetic susceptibility, and
- thermal expansion.

Microscopic details are investigated by

- angle-resolved and -integrated photoemission spectroscopy, which probes electronic structure near and below the Fermi energy;
- nuclear magnetic resonance, which measures the local electronic susceptibility, local crystalline symmetry, and spin dynamics;
- muon-spin resonance, which senses very weak magnetic transitions;
- neutron and x-ray diffraction at ambient and high pressures, which give detailed structural information, including stoichiometry, defect structure, static and dynamic order/disorder, valence ordering, and site-specific Debye-Waller factors;
- resonant ultrasound spectroscopy, which allows complete determination of elastic properties;
- ambient and very high-pressure Mössbauer spectroscopy, which provides microscopic valence and lattice-dynamic information; and
- ion-beam techniques, which use a Van de Graaff accelerator to determine the chemical composition and structural integrity of a sample.

P-10: Condensed-Matter and Thermal Physics

Joe D. Thompson, Group Leader

The thoroughness with which these techniques characterize a material's properties is essential for linking materials science to microscopic understanding and for bridging the gap between materials synthesis and theory.

In addition, nonlinear dynamics and chaos are investigated in model fluids, for instance, ^3He -superfluid ^4He mixtures. The simultaneous application of a thermal gradient and centrifugal force to the fluid creates vortex structures that can be either stable or produce turbulent convection, depending on parameter values. These model systems provide laboratory examples of problems common to many disciplines, including dendritic growth or directional solidification in materials and fluid dynamics of atmospheric circulation.

Besides these basic research areas, four programs in P-10, though fundamental, have more applied goals. One project explores the design and development of novel heat engines, using principles of thermoacoustics and working substances that range from ^3He -superfluid ^4He mixtures to more conventional liquids near their critical point. Important advantages of these approaches are the elimination of moving parts and sliding seals in reciprocating engines, as well as the elimination of working fluids harmful to the atmosphere. Consequently, this program is particularly interesting to several United States industries. Another

program involves the development of cryogenic deuterium-tritium (D-T) targets for the national ICF Program. The high starting density of cryogenic fusion targets allows implosions to reach the desired final density with lower drive energies. A number of outstanding physics and technology questions, especially D-T thickness and density uniformity, are being addressed. Nondestructive testing, based on resonant ultrasound inspection, is an applied program that has developed out of basic research on elastic properties of materials. This approach offers extreme sensitivity to defects, is very efficient relative to conventional techniques, and has a number of potential applications of interest to the Air Force and several industrial corporations. Finally, electrical transport in quantum-confined systems is being studied to provide a basic understanding of transport processes and to enable new approaches to advanced computing technologies.

The programs in P-10 often involve collaborations with a number of other Laboratory Divisions and organizations, including the Center for Materials Science, the Center for Nonlinear Studies, the Superconducting

This capacitance dilatometer (inset) measures the thermal expansion of small (1 to 10 mm) single crystals. Length changes as small as 10^{-13} m can be detected by measuring the change in capacitance between two parallel plates. Postdoctoral fellow David Mandrus prepares the dilatometer for cooldown. The fully automated measurement system permits the temperature to be swept slowly from 2 K to 330 K while the capacitance of the cell is simultaneously measured. A complete measurement takes about 30 hours.

Technology Center, the Manuel Lujan, Jr., Neutron Scattering Center (LANSCE), and the National High Magnetic Field Laboratory. Extensive collaborations also exist with the University of California, United States industrial laboratories, and other national laboratories.

P-11 is devoted to research in nuclear and particle physics, mostly at LAMPF where we presently conduct research in pion and electroweak physics. The group is a combination of former MP-Division research groups, primarily MP-4 and MP-10, with a few personnel from other groups. The experimental program at LAMPF is expected to continue until 1995. After that time, a small number of particularly appropriate experiments may continue, but the bulk of the group's effort will more likely turn to activities outside the local accelerator complex.

The pion program uses a number of charged-particle spectrometers, which are maintained by the group. Users come to LAMPF after they are approved with advise from a program committee. These groups conduct experiments with this equipment with the help of P-11 staff members and technicians.

The neutral meson spectrometer (NMS), which was commissioned in 1993, will take data on π^0 reactions with excellent energy and mass resolution to detect and measure the π^0 's. Our program will exploit pion research using the NMS detector. This activity will dominate the LAMPF Experimental Area A through the 1995 running period.

The electroweak program consists of experiments in the stopped-muon channel, which produces one of the highest-intensity muon fluxes anywhere. The MEGA experiment [Muon (decays to) an Electron and a GAMMA ray] is a search for the reaction $\mu \rightarrow e + \gamma$, which has not been observed and is one of the most stringent limitations on lepton-family number conservation. In the next two years, this experiment will set a limit of about 5×10^{-13} on the branching ratio for this reaction, provided of course the reaction is not observed. In addition, P-11 is collaborating with Princeton University and Syracuse University to measure the induced pseudoscalar coupling constant by absorbing μ^- on polarized ^3He .

The liquid scintillator neutrino detector (LSND), commissioned in 1993, has taken interesting data using neutrinos largely from the LAMPF beam stop. The primary focus of the LSND experiment is to search for neutrino oscillations, but the detector will also measure the scattering of ν_μ on protons and neutrons. Such measurements will cast light on the question of the spin structure of nucleons.

The beam from LAMPF is also used to provide a pulsed beam of neutrons at LANSCE. A P-11 experiment is using polarized neutrons from this source to investigate parity violation in heavy

P-11: Nuclear and Particle Physics

D. Hywel White, Group Leader

This view of the central portion of the MEGA detector, figuratively known as Snow White and the Seven Dwarves, shows the detector geometry that picks up electron signals from $\mu \rightarrow e + \gamma$ reactions.

RN92-158-01

**P-14: Fast-Transient Plasma
Physics**

Mary Y. Hockaday,
Acting Group Leader

nuclei with great precision. These data in turn will form the basis of a search for the time-reversal violation in these nuclei.

In collaboration with P-2, we are pursuing an experiment to investigate antiquark distributions in protons and deuterons at Fermilab. The quark and antiquark distributions in the nucleon sea was thought to be symmetrical. Violations of the Gottfried sum rule, which made it clear that this is not so, have led to proposals for investigation of the detailed structure. We are also collaborating with P-2 in an initiative to develop the muon identification capabilities of the PHENIX detector at the relativistic heavy ion collider (RHIC) at Brookhaven National Laboratory. This work will benefit both the main goals established for this detector and studies of the effect of spin in the scattering of polarized protons in RHIC.

P-11 has operated a detector array called CYGNUS at LAMPF to investigate point sources of cosmic rays. Initially, this project began as an effort to exploit the ability of neutrino detectors at LAMPF to detect muons in coincidence with surface cosmic-ray showers, but it has led to a proposal for the construction of a new detector (MILAGRO) to be built at Fenton Hill. The detector consists of an array of phototubes placed in a large pond previously used as a reservoir for the hot, dry rock geothermal project at Fenton Hill. This extraordinarily cost effective use of the facility is very promising for extending the capabilities of ground-based arrays for the detection of neutral cosmic rays.

The mission of Group P-14 is to conceive, execute, and analyze experiments in the nuclear-weapons program to maintain and enhance the nation's nuclear-deterrent capability and to address other national-security issues.

To carry out its primary mission in the nuclear-weapons program, P-14 executes 20 to 30 major physics experiments each year. In years past, these experiments were primarily on underground nuclear-weapons tests with a gradual shift in emphasis to AGEX. With the advent of the testing moratorium, we accelerated our diversion into AGEX activities. Experiments in AGEX provide the challenging opportunities that we need to keep the interest of the key physicists in the experimental nuclear-weapons physics arena.

Experiments executed in AGEX profit from the traditional strengths of P-14: measurements of gamma-rays, x-rays, neutrons, and optical and electromagnetic phenomena. There are ongoing efforts at the Livermore Nova laser, at the Sandia Saturn pulser, and at Los Alamos AGEX facilities. P-14 AGEX experiments include neutron time-of-flight (TOF) fusion-temperature measurements, x-ray spectroscopy, plasma interferometry, and measurements of currents and fields generated by capacitive and high-explosive-driven pulsed-power generators. As in the underground work, some AGEX endeavors are devoted to basic physics (i.e., the ongoing P-14 opacity measurements at Nova).

A new area of activity for us is in collaborations with laboratories in Russia. P-14 physicists and technicians characterized the radiative output of Angara-5 implosion experiments at Troitsk using a time-resolved x-ray spectrometer. We are also collaborating on explosive pulsed-power experiments with the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) at Arzamas (designated Arzamas-16). Some of these experiments, in which we measured extraordinarily high magnetic fields, took place here at Los Alamos. In other experiments at VNIIEF, we are measuring high currents, x-rays, and neutron production.

One of the strengths of the group is its knack for exploiting diverse and extraordinary physical effects for experimental diagnostics, including

Compton scattering, transition and Cerenkov radiation, Faraday rotation, and the Kerr and Pockels effects. Another is the development of state-of-the-art enabling technologies for high-bandwidth measurements by the P-14 Electro-optics and Electronics Section. Examples of techniques pioneered and developed in P-14 include high-bandwidth, fiber-optic analog data links, which are based on interferometric electro-optic transducers; ultrahigh-speed, time-interval meters with 10-ps resolution; high-speed optical receivers; and ultrafast oscilloscopes. P-14 maintains its ability to execute experiments at remote locations through the sophisticated mobile data-recording stations of its High-Speed Transient Recording Section and through its extensive inventory of modern recording instrumentation. Finally, its Data Analysis Section supports the group's experimental efforts by providing computer-system support and data-reduction and analysis services for the P-14 physicists.

RN93-217-011

Group P-14's Faraday rotation diagnostic, which measures the total current at various locations in the Procyon system, has the unique advantage in that it requires no electrical coupling to Procyon. The small closed boxes contain battery-operated laser diodes that launch polarized 670-nm or 830-nm light into a twisted optical fiber. The polarization is rotated by the magnetic field as the light circles the current path in Procyon, thus providing a measurement of the current. The amount by which the polarization is rotated is analyzed with optical elements in the black boxes shown in the figure. The equipment is located behind piles of sandbags and a blast shield to protect it from the high explosives and debris created by Procyon.

Historically, a significant fraction of the experimental program in P-15 has centered around the definition, implementation, and analysis of experiments in support of Los Alamos underground nuclear tests. Group members work closely with nuclear-weapons designers to perform a diagnostic program, providing constraints on design models for enhancing predictive capability and physics interpretation of performance. The emphasis in experiments has been on absolute-neutron-flux measurements and a broad spectrum of imaging and spectroscopy measurements of neutrons, gamma rays, and x-rays.

Successful designs for nuclear-test experiments require solving problems related to the survival of experiments conducted in harsh nuclear environments. In performing such experiments, group members participate in the development and use of remote-controlled instrumentation. This equipment includes large format, streak and intensified, fast-scan video cameras; image-data-capture systems; fiber-optic data transmission; high-sensitivity,

P-15: Applied Physics Experiments and Imaging Measurements

Nicholas S. P. King, Group Leader

CN94-210

Nick King (left) and Tom McDonald participate in Group P-15's exhibit booth at the Armed Forces Communications and Electronics Association Conference in San Diego, California. P-15's capabilities in high-speed imaging are displayed.

megasample rate digitizer systems; and gigahertz-oscilloscope, data-recording systems. Such instrumentation allows group members to obtain absolute nuclear-radiation-flux measurements, spectroscopy measurements, the imaging of nuclear radiation and optical sources in the nanosecond time domain, a variety of temperature diagnostics, and precision hydrodynamic-yield determination (CORRTEX). By extensively interacting with numerous electro-optics and electronics companies, P-15 has maintained the necessary state-of-the-art capabilities to address constantly changing requirements in weapons-physics experiments.

Most recently, with the underground-nuclear-test moratorium at the Nevada Test Site (NTS) in effect, the unique capabilities in P-15 now provide state-of-the-art imaging, as well as high-precision and high-sensitivity measurement techniques, at AGEX facilities. We are actively participating in experiments at the Procyon Facility, the Trident Facility,

the Pegasus II Facility, the Weapons Neutron Research (WNR) Facility, the Ion Beam Facility (IBF), and local high-explosive firing sites. Emphasis has now shifted to ultrahigh-resolution ultraviolet- to infrared-wavelength and x-ray-imaging experiments. Our unique, high-sensitivity measurement and recording techniques for nuclear radiation can be readily applied to low-level signals often encountered in the AGEX experiments, as well as in possible hydronuclear experiments.

To investigate nuclear, atomic, and plasma-physics phenomena relevant to changing weapons program requirements, group members actively participate in basic and applied-physics experiments at Los Alamos and at a number of other national and international laboratories and universities. These experiments permit P-15 to maintain contact with evolving experimental techniques and ideas that may be applied to cross-disciplinary or "dual-use" programs. Neutron-physics experiments are routinely performed. These experiments have, for example,

recently contributed to the evolving Accelerator Transmutation of Waste (ATW) project and nuclear-weapons NTS data interpretation. P-15 is also involved in global-climate-modeling projects through the Ground-based Earth Observing NETWORK (GEONET). GEONET involvement is both theoretical through joint P-Division/X-Division collaborations and experimental through the development of a lidar-remote-fielding capability.

Another experiment involves the development of a trap and delivery system for ultralow-energy antiprotons at CERN. This development will be applied to nuclear- and atomic-physics problems of international interest (e.g., antihydrogen formation, antimatter-gravity studies, microfission-capsule experiments, fission processes, and relative

The mirror (right) is part of a P-15/DX-15 image relay system used to record 50-ns snapshots of the Procyon explosively driven pulsed-power experiments. Group P-15 is applying imaging technology from the underground test program to the evolving Los Alamos AGEX II Program.

neutron/proton distributions in nuclei). A new initiative is the development of a quantum cryptography capability requiring ultrafast timing with single-photon detectors.

Use of P-15's expertise in CORRTX and hydrodynamic-yield modeling provides an ongoing unique effort that provides a physics-based approach for the potential discrimination between chemical and/or natural seismic phenomena versus nuclear explosions. CORRTX expertise is an essential part of the negotiations conducted by the United States for international nuclear-yield verification. This effort involves the identification of possible nonnuclear- versus nuclear-seismic-signal signatures for nonproliferation initiatives.

P-15 maintains a flexible computing capability within the group to support experimental, theoretical, and data-archiving efforts. A sophisticated workstation network, the largest in P Division, with significant computing capabilities has been developed. In-house computers, which include a network of SUN and HP workstations, a classified VAX 11/750, and numerous PCs, have both classified and unclassified links to the Central Computing Facility (CCF) through the Laboratory's Integrated Computer Network. The group also uses the CCF with its Cray computers.

Group P-15's present expertise in ultrafast, intensified, fast-optical-shutter imaging systems is expanding to provide experimental capabilities in x-ray and optical measurements for an evolving biotechnology program, the ICF Program at Nova, medical x-ray imaging, and very high frame-rate-intensified imaging for military laser range/mine detection applications. These capabilities form the basis for present and future industrial-technology and Department of Energy/Department of Defense (DoD) cooperative efforts.

The Los Alamos IBF, operated by P-15, produces general-purpose, precision ion beams for a wide variety of users and experiments. Resources at the facility include a vertical Van de Graaff accelerator capable of operating at potentials up to 8 MV and an HVEC model FN tandem Van de Graaff accelerator operating up to 11 MV. The vertical accelerator can provide extremely stable low-energy ion beams. Coupling it to the FN tandem results in a unique, higher-energy ion beam. Its precision neutron- and ion-production capabilities have been regularly used to develop and calibrate detectors for use in underground nuclear diagnostics and are critical to maximizing diagnostic return from proposed hydronuclear tests. New technologies, such as an enhanced gamma-ray-sensitive imaging system for hydrotests and neutron/gamma-ray discrimination systems for hydronuclear tests, are being evaluated. The IBF has also been used to develop and calibrate a variety of detector systems for AGEX initiatives, as well as for ongoing collaborative Russian experiments.

George Yates examines the set up of a developmental CCD (charge-coupled device) that is being tested in the solid-state-imager test station used in P-15 to characterize new CCDs at high-pixel read-out rates.

P-17: Neutron and Nuclear Science

Paul W. Lisowski, Group Leader

Group P-17 operates and performs research at the WNR Facility at LAMPF. The WNR Facility has both a high-intensity spallation neutron source (Target-4) and a low-intensity, low-return area (Target-2) that allow direct access to the LAMPF proton beam.

The Target-4 source produces the highest flux of neutrons (from 1 to 800 MeV) in the world. In addition, P-17 has three beamlines at LANSCE for nuclear-physics research using neutrons from thermal energy to about 100 keV. Presently, there are six fully instrumented neutron flight paths for TOF research. Some of the activities under way include a program to determine level densities through the investigation of (n,charged particle) reactions from 1 to 50 MeV, giant-resonance measurements using charge exchange, measurements of neutron elastic scattering from 50 to 200 MeV, fast-neutron-capture and gamma-ray-production experiments, fission-cross-section measurements to 200 MeV, neutron-proton bremsstrahlung experiments, and investigations of detector performance to improve our understanding of underground-nuclear-test data previously obtained at the NTS.

A major new initiative for P-17 is the development of a flight path for use in simulating cosmic-ray-generated neutron effects on aircraft electronics. A collaborative program with Honeywell-Boeing is under way. In addition, the Defense Nuclear Agency has funded P-17 to develop a preconceptual design for an accelerator-based subcritical assembly for simulating radiation effects from nuclear weapons. Such a facility may be an important aid in evaluating future DoD system performance in radiation environments. Protons with energies from 113 to 800 MeV are available for experiments carried out at Target-2. This area is being used for radionuclide-production, tritium-efficiency experiments for the Accelerator Production of Tritium Program, ATW experiments, and studies of radiation damage and single-event-upset phenomena in electronics.

Group P-17 also operates three beamlines at LANSCE, an intense source of neutrons from the thermal- to keV-energy range. Presently, P-17 has three major activities under way at LANSCE. With collaborators from LAMPF, other Los Alamos groups, and several universities, P-17 has developed a polarized neutron beam using a polarized proton target;

group members are using the beam to search for parity violation as manifest in neutron-resonance phenomena. Later experiments will expand the research to include a search for time-reversal symmetry violation. P-17's other major activities involve measurements of (n,charged particle) and (n,gamma) cross sections on radioactive targets for programs in nuclear astrophysics and defense and in the development of a novel neutron-transmission technique for determining dynamic material properties.

Robert Haight (left) and Stephen Sterbenz of Group P-15 consult with Herbert Vonach of the University of Vienna on the array of detectors used to study (n,charged particle) reactions at the WNR Facility.

Recent Weapons-Physics Experiments on the Pegasus II Pulsed Power Facility

J. S. Ladish (P-1), M. Y. Hockaday (P-14), and the Athena Liner Team

Dave Scudder examines the target-mounting assembly after a shot on Pegasus II.

The Pegasus II Pulsed Power Facility is part of the Laboratory's AGEX II (AboveGround EXperiments) Program. With the reduction in test-site-related experiments, Pegasus II has begun to play an increasingly important role in providing an experimental means of addressing issues relevant to the weapons-physics community. This past year, the first campaign dedicated to investigating a weapons-physics issue was undertaken at the Pegasus II Pulsed Power Facility. This campaign, referred to as the Liner Series, was aimed at developing a driver that would produce shock pressures of interest to weapons design. The specific goals of this first series were to uniformly accelerate a solid liner to an implosion velocity of $3 \text{ mm}/\mu\text{s}$ and to diagnose its time-dependent shape, velocity, electrode-to-liner interface, and density. The series consisted of three shots at roughly two-week intervals: Liner 0 on April 5, 1993; Liner 1 on April 15, 1993; and Liner 2 on May 7, 1993 (Figs. 1 and 2). The liners used in these experiments consisted of aluminum cylinders that were 0.4 mm thick, 2 cm high, and 4.8 cm in diameter.

The diagnostics used to measure the performance of the liner included an optical framing camera; a "two-eyed," high-resolution gated camera system; a triple-axis radiographic system; a flux monitor; and 24 optical pins located on a 2.8-cm -diam aluminum cylinder inside the liner. On Liner 1, radial radiographs were taken at $7.02 \mu\text{s}$ and $7.71 \mu\text{s}$; on Liner 2, radial radiographs were taken at $6.87 \mu\text{s}$ and $7.57 \mu\text{s}$. From these radiographs, we can determine an implosion velocity. Figs. 1 and 2 show example radiographs taken on Liner 1 and Liner 2, respectively. Data obtained from all the radiographs for both liners are summarized in Table 1. As can be seen from the data in Table 1, the experiments produced an average liner velocity of approximately $3 \text{ mm}/\mu\text{s}$. Interestingly, the data obtained in the Liner 1 experiment show that the liner was accelerated off-axis because of asymmetries in the magnetic pressure that arose from an asymmetric current feed to the liner. This asymmetry was corrected in Liner 2, and the result was a near-perfect symmetric liner implosion on axis.

Fig. 1. This radial x-ray photograph of Liner 1 was taken during the implosion of the liner at $7.71 \mu\text{s}$ after the start of the current pulse.

Fig. 2. This radial x-ray photograph of Liner 2 was taken during the implosion of the liner at $7.57 \mu\text{s}$ after the start of the current pulse.

The success of these first weapons-physics experiments on the Pegasus II system has helped to promote greater interest in AGEX II experiments on the part of the weapons designers and has stimulated discussions and proposals for further experiments in the upcoming year. We expect that approximately one-half of the shots fired on the Pegasus II system next year will be fired in support of weapons physics.

Table 1
Radius and Velocity

Liner 1

Description	Timing (μ s)	Radius (cm)	Average Velocity (mm/ μ s)
Port 4 Platts 1	7.020 $\pm$ 0.025	1.988 $\pm$ 0.008 (outer)	3.3
Port 7 Platts 2	7.711 $\pm$ 0.025	1.758 $\pm$ 0.016 (outer)	
Axial	7.457 $\pm$ 0.025	1.825 $\pm$ 0.011 (center)	

Liner 2

Description	Timing (μ s)	Radius (cm)	Average Velocity (mm/ μ s)
Port 4 Platts 1	7.572 $\pm$ 0.025	1.740 $\pm$ 0.024 (outer)	2.8
Port 7 Platts 2	6.874 $\pm$ 0.025	1.933 $\pm$ 0.024 (outer)	
Cohu+Nal	7.527 $\pm$ 0.025	17.3 $\pm$ 0.5 (outer)	
Axial	7.643 $\pm$ 0.025	1.655 $\pm$ 0.023 (center)	

Operation of a Large-Scale Plasma Source Ion Implantation Experiment

B. P. Wood, D. J. Rej, I. Henins, R. J. Gribble, W. A. Reass (P-1), R. J. Faehl (X-5), M. A. Nastasi, K. C. Walter (MST-4), and Collaborators from General Motors Research Laboratories and the University of Wisconsin

Implanting gaseous ions into metal surfaces creates a thin surface layer of modified material, which increases the hardness of the metal, reduces friction, improves wear, and aids in corrosion resistance. Plasma source ion implantation (PSII) offers a simple, cost-effective alternative to conventional ion-beam implantation processes. The PSII process is illustrated in Fig. 3. A metal workpiece is immersed in a weakly ionized plasma that contains the ions to be implanted. The workpiece is then subjected to high-voltage negative pulses. During each pulse, the positive ions are accelerated toward the workpiece and implanted in its

Fig. 3. In the PSII process, positive ions in a weakly ionized plasma are accelerated toward the workpiece and implanted in its surface by an applied, negative high voltage.

surface. Because the implant is performed over the entire surface simultaneously, the high implant currents achieved greatly reduce the total time required to treat an object. PSII eliminates the expensive, low-current accelerators used in conventional ion implantation; furthermore, there is no need to mask or manipulate the workpiece. Consequently, the cost of PSII equipment is much lower than it is for conventional beam-implantation equipment.

PSII has successfully been used to treat small, individual parts, such as drills, punches, dies, and orthopedic implants. Los Alamos has teamed with General Motors Research Laboratories and the University of Wisconsin in a four-year \$13 million Cooperative Research and Development Agreement (CRADA) to demonstrate that PSII can be scaled up to an industrially useful size to allow for the simultaneous treatment of hundreds of small parts or single large parts. Surface areas in excess of 4 m² have already been implanted at Los Alamos.

The PSII experimental facility, located in P-1, consists of a 4.6-m-long, 1.5-m-diam cylindrical vacuum chamber (Fig. 4), which was formerly used in the Los Alamos Magnetic Fusion Research Program. A plasma of density in the 10¹⁴ m⁻³ range is created in 0.1-mtorr nitrogen with a radio-frequency source coupled to an antenna inside the PSII chamber (Fig. 5). The high-voltage pulse used to accelerate ions is supplied by a modulator that is based on the Ground Test Accelerator technology, developed by AT (now AOT) Division as part of the Los Alamos Strategic Defense Initiative Program. The PSII modulator can supply 50 A of current and 125 kV of energy with 20-ms pulses at a frequency of 2,000 Hz.

Fig. 4. The Los Alamos PSII facility, once used for magnetic-fusion research, consists of a 4.6-m-long, 1.5-m-diam cylindrical vacuum chamber.

CN93-520

Fig. 5. A cylindrical aluminum workpiece is implanted in a nitrogen plasma.

A number of constraints and inefficiencies must be overcome before the expected advantages of PSII can be realized. Even with over 50 A of current available, the experiment is actually limited in current because of the large surface areas that must be implanted. These large areas make the implantation of recessed areas on the surface of the metal difficult. A proposed upgrade of the modulator will supply 300-A pulses, which will thus help alleviate this constraint. A large portion of the total current is made up of undesirable secondary electrons. Experiments are under way to determine whether this inefficiency can be reduced by magnetically insulating the workpiece. A final constraint is imposed by explosive-electron field emission from the workpiece, which limits the operating voltage.

Our first implanted industrial parts, a series of 64 high-speed, steel cutting tools supplied to us by Jasco Tools, Inc., Rochester, New York (Fig. 6), are currently being tested in a General Motors fabrication facility. The results of this test will allow us to tune our operating parameters in an effort to improve the PSII process.

We are discussing applications for the PSII technology with other potential industrial partners. One area of great interest is the replacement of wet-process chrome plating with either gaseous species or direct metal-ion PSII. Wet-process plating uses hazardous and soon-to-be-banned chemicals and produces wastes that are difficult and expensive to dispose of. In contrast, PSII is an environmentally conscious "dry" process that produces little or no hazardous by-products.

Fig. 6. Our first industrial implanted parts are a series of 64 high-speed, steel cutting tools for the General Motors Corporation.

Production of Charm and Beauty Mesons at Fermilab

M. J. Leitch, J. Boissevain, T. A. Carey, D. M. Jansen, R. G. Jeppesen, J. S. Kapustinsky, D. W. Lane, J. W. Lillberg, P. L. McGaughey, J. M. Moss, J. C. Peng (P-2), and Collaborators from Abilene Christian University, the University of Chicago, Fermi National Accelerator Laboratory, the University of Illinois at Chicago, Lawrence Berkeley Laboratory, Northern Illinois University, the University of South Carolina, and the Institute of Physics at Taiwan

Since the discoveries of the J/ψ meson, which contains the charm quark (discovered in 1974), and of the upsilon meson, which contains the beauty quark (discovered in 1977), much of the effort in high-energy physics has been devoted to the study of these mesons and other particles that contain these quarks. The charm and beauty quarks are the heaviest of the most fundamental building blocks of matter currently known and are bound together by gluons to form various mesons. As part of understanding these heavy quarks, we must study how they are bound together into the mesons; how this binding is modified if the meson is formed in the interior of a massive nucleus rather than in an isolated nucleon; how they are produced; and how the different quarks, including the lighter up, down, and strange quarks, couple to the heavier quarks. To gain a deeper understanding of these heavy quarks, we have measured their production cross sections; the probabilities for their decay into various lighter particles, like pions and kaons; and the modification of their production when they are produced in heavy, instead of light, nuclear targets.

Our investigations began with Experiment 772 (E772) in 1987 at Fermilab where we measured the nuclear size dependence of the production of the J/ψ and upsilon mesons by 800-GeV protons incident on stationary nuclear targets. These measurements indicated that the number of these mesons produced per target nucleon decreases dramatically as one goes to larger nuclei. Similar results were obtained in other experiments in which a pion beam was used instead of a proton beam. However, even though there were a number of possible explanations for the suppression in heavy nuclei, it is still unclear which mechanisms are actually responsible. One possibility has to do with the production mechanism for the mesons. The dominant mechanism is the fusion of two gluons, one from the incident proton and the other from a nucleon in the stationary nucleus. Modifications of the population of gluons in a nucleon within the nucleus relative to that for an isolated nucleon could cause a change in the probability for producing the mesons. On the other hand, the effect might come after the meson is produced but while it is leaving the vicinity of the nucleus. For example, it could interact with other nucleons in the nucleus or with debris caused by the incident proton when it entered the nucleus and thereby be broken up into lighter particles before it could be observed outside the target. Other more exotic mechanisms, such as a pre-existing presence of charm quarks in the incident proton, might also play a role. To help identify the most important mechanisms, we can compare the production of different mesons that contain the charm quark. The J/ψ contains both a charm and

an anticharm quark; however, a D meson contains only one charm quark coupled with a lighter quark. Some of the mechanisms that could be responsible for loss of the J/ψ while leaving the nucleus would be absent for the D meson. To help make this comparison, we have measured the nuclear size dependence for the production of D mesons in one part of our newest experiment (E789).

The experimental measurements were made with a large pair spectrometer at the Fermi National Accelerator Laboratory near Chicago. An 800-GeV proton beam strikes a stationary beryllium or gold target. When an opposite-sign charged pair of particles (e.g., a positive pion and a negative kaon) is produced in the process, it is analyzed by a series of very large magnets instrumented with scintillation and drift-chamber detector planes, which accurately measure the trajectory of each particle. For the E789 measurements, a very thin-strip target is used along with a precision silicon-vertex detector, which is located just downstream of the target to isolate events that originate from a point downstream of the target by several millimeters. When D or B mesons are created in the target, they have a lifetime of a few picoseconds, which allows them to travel a few millimeters downstream before decaying into the two charged particles that we detect. We then reconstruct the direction, energy, and mass of the mesons. The resulting D meson mass spectrum shows a smooth background over a large range in mass and a peak at the D meson mass. In our 1991 run, a new high-speed data-acquisition system allowed us to record about 1,500 tapes full of event data. The analysis of this huge amount of data, which has so far consumed over a year of time, is being handled with high-speed UNIX computers and multiprocessor systems.

About 4,000 $D^0 \rightarrow K\pi$ events have been reconstructed from the recorded data for gold and beryllium targets (Fig. 7). The peak at 1.86 GeV, which has a resolution of about 5 MeV sigma, contains the D mesons that were produced. The resulting production cross section of about 22 μb is found to be consistent with that seen in earlier measurements. Also we saw no change in the number of D mesons produced per nucleon between the light beryllium nucleus and the heavy gold nucleus, which is in agreement with other experiments where D mesons were produced with pion beams instead of a proton beam. These new observations suggest that the suppression seen for J/ψ production in earlier experiments is probably caused largely by effects on the J/ψ after it is produced, e.g., absorption by the nucleus or dissociation by interactions with debris created by the proton as it enters the nucleus. Such mechanisms would have little effect on the D mesons.

Most of the recorded data obtained in our 1991 run was taken at settings optimized to observe the production of B mesons, which contain the beauty quark. The cross section for producing B mesons is roughly a factor of 1,000 smaller than that for producing D mesons. So the number of B mesons that we can observe, even with higher proton beam intensities and longer running times, is substantially smaller. We observe the B meson by its decay into J/ψ , and the J/ψ is detected by its decay into an opposite-sign pair of muons.

Fig. 7. This mass spectrum, with a peak at 1.86 GeV, corresponds to the production of neutral D mesons and their decay to a pion and a kaon.

Fig. 8. This mass spectrum, with a peak at 3.1 GeV, corresponds to the production of b quarks and their decay into a J/ψ and an unobserved light meson (e.g., a kaon).

The resulting mass spectrum (with about 65% of the data analyzed) is shown in Fig. 8. The peak at the J/ψ mass of 3.1 GeV contains the events that come from decays of the B to a J/ψ and has a width of less than 10 MeV sigma. A smooth background, caused by the creation of a B meson pair with each B meson decaying to give an independent muon, lies underneath the peak. About 22 events lie in the peak. These events correspond to a preliminary cross section that is in agreement with expectations of about 10 nb from current theoretical calculations. This cross-section measurement is important for planning future experimental programs that would use proton beams to create much larger numbers of B mesons to study details of their decays. In future analyses of our existing data, we will also search for direct decays of the B mesons into lighter particles that contain neither the beauty nor the charm quark.

Sudbury Neutrino Observatory

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The Sudbury Neutrino Observatory (SNO), a collaboration consisting of 11 institutes from Canada, the United Kingdom, and the United States, is a major activity of the P-3 Weak Interactions Group. The goal of SNO is to measure the flux and spectral shape of electron neutrinos of energy 5 MeV, which are produced in the fusion processes that power the Sun. In addition, SNO will measure the total flux of all neutrino flavors above a threshold of 2.2 MeV. This second-generation solar-neutrino detector will provide unprecedented information concerning neutrino production in the Sun and, thereby, a definitive explanation concerning the origin of the so-called solar-neutrino problem (SNP).

The SNP refers to the long-standing discrepancy between the experimentally measured and theoretically predicted solar-neutrino flux. Recent results from SAGE (a gallium-radiochemical neutrino detector in which P-3 is also a major participant), GALLEX (another gallium experiment), and Kamiokande (a Japanese water-Cerenkov neutrino detector) provide further experimental support for the original chlorine radiochemical neutrino detector, which for 20 years has reported a solar-neutrino flux of approximately one-third of that predicted. Solar theory is unable to reconcile these differences and thus the question remains: Is the theoretical model of the Sun in error, or do neutrinos possess properties beyond those described in the standard model of particle physics?

One possible property of the neutrino, which may elegantly resolve the SNP, arises naturally in some extensions of the standard electroweak model—that is, the neutrino may have a nonzero mass. This neutrino property would be the first indication of exciting new physics beyond that currently described by the standard model. If the neutrino flavors, ν_e , ν_μ , and ν_τ , are expressed as combinations of different mass eigenstates, then as the neutrinos propagate through space the relative phases of the various mass eigenstates will change, and thus the neutrino flavor will likewise change through a process known as “vacuum oscillations,” which occur as the neutrino travels from the Sun to the Earth.

Oscillations may be greatly enhanced when neutrinos pass through matter such as the Sun or Earth because the ν_e interact with electrons via the charged current, which does not affect the ν_μ and ν_τ neutrinos. These flavor changes, referred to as “matter oscillations,” may be undetectable (as in the case of the radiochemical experiments, which are only sensitive to ν_e) or may have a reduced sensitivity (as in the case of the water-Cerenkov detectors). Either of these oscillation scenarios would be interpreted as a reduced flux by the first generation of solar-neutrino detectors. By comparing the flux of ν_e (the flavor expected from the Sun) with the total flux of all neutrino flavors as measured by SNO, we will be able to determine whether neutrinos are undergoing flavor oscillations. Further information on the type of oscillation will be obtained by looking for distortions in the ν_e spectra.

Observations of distant galaxies suggest that a supernova may occur in our galaxy on average every 30 ± 7 years, but it is hidden from observation by dense matter at the heart of the galaxy. Such matter would hardly perturb the neutrino flux, which carries some 99% of the energy of the collapsing star. The SNO detector would detect over 700

neutrino events from a supernova located near the center of our galaxy and would thus allow for a stringent test of stellar-collapse theory. Timing the arrival of the different flavors of neutrinos allows us to set limits of 50 eV on the mass of the ν_μ and ν_τ . Because SNO has a design life of at least 10 years, the possibility of it detecting a supernova is not insignificant.

The unique features that allow SNO to access this wealth of physics is the presence of heavy water (D_2O), a deep underground location shielded from cosmic rays, and meticulous attention to the radiopurity of the detector materials. The laboratory is located in Sudbury, Canada, at a depth of 6,800 ft in the INCO Creighton mine (Fig. 9). This depth, which makes SNO the second deepest laboratory in the world, helps to reduce background interference from cosmic rays by 8 orders of magnitude. The water-Cerenkov detector consists of 1,000 tonnes of D_2O , which is contained in a spherical 40-ft-diam acrylic vessel. Acrylic was chosen for its radiopurity, good transmission of the Cerenkov light, and relative ease of construction (Fig. 10). This vessel is surrounded by 7,000 tonnes of light water (H_2O), the primary purpose of which is to shield the central D_2O volume from the natural radioactivity of the surrounding rock. Contained in this H_2O is a stainless-steel 60-ft-diam geodesic structure that supports 9,600 photomultiplier tubes (PMTs) each 8 in. in diameter. The PMTs were selected for their excellent timing resolution and constructed from a special low-radioactive glass. The light-collection ability of the PMTs is enhanced by equipping each with a nonimaging Winston cone (Fig. 11). Thus, about 56% of the surface enclosed by the geodesic structure is sensitive to single photons of light. A trigger threshold of 5 MeV is achieved by maintaining the temperature of the water at 10°C to reduce the random, or dark, noise of the PMTs; selecting detector materials for their radiopurity; purifying the water to better than 1 part in 10^{15} of uranium and thorium; and hermetically sealing the detector against an ingress of radon from the laboratory atmosphere.

Three primary reactions are available for the detection of solar neutrinos. In neutrino-electron elastic scattering,

$$\nu_x + e \rightarrow \nu_x + e,$$

all neutrino flavors can participate, but the elastic scattering is dominated by ν_e because these neutrinos can interact by both the charged and the neutral current. The recoil electron gives good directional but

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Fig. 9. The cavity for the SNO detector is being excavated at a depth of 6,800 ft in the INCO Creighton mine. The finished cavity will be 80 ft wide and 110 ft deep.

CN94-214

Fig. 10. In this artist's impression of the SNO detector, the 40-ft-diam acrylic vessel, which contains 1,000 tonnes of heavy water, is shown with a section of the geodesic structure on which the 9,600 PMTs are mounted. The array of tubes inside the sphere are 3He proportional detectors. These detectors are being developed by P-3 and, if used, will greatly enhance the power of the observatory. Inside the vessel, a small submersible vehicle (shown inside the vessel and at the right) is deploying one of the 3He detectors. This technique is currently being demonstrated at Los Alamos.

Fig. 11. Each of the PMTs will be equipped with a light-collection Winston cone as shown in this photograph.

poor spectral information. The event rate, assuming a standard solar flux, is 1,100 per year for a 5-MeV threshold. A second reaction is the charged-current process,

$$\nu_e + d \rightarrow p + p + e^-,$$

whereby only ν_e can participate. All the energy of the incoming neutrino, minus the Q-value for the reaction (1.4 MeV), is carried by the electron. This is an excellent reaction for studying the energy distribution of neutrinos produced by the fusion reactions in the Sun. The event rate, assuming a standard solar flux, is 9,750 per year for a 5-MeV threshold. Finally, the neutral-current disintegration of the deuteron,

$$\nu_x + d \rightarrow \nu_x + p + n,$$

induced equally by all flavors of neutrinos above the deuteron-binding energy of 2.2 MeV, is used to measure the total flux of all flavors of neutrinos. The reaction is detected by capturing the free neutron on the chlorine added to the D₂O. The 8.6-MeV capture gamma ray subsequently emitted by the chlorine nucleus is then measured by detecting the Cerenkov light. The event rate, assuming a standard solar flux, is 2,800 per year for a 5-MeV threshold. This reaction is vital for determining whether the SNP is a problem with the theoretical model of the Sun or a new property of the neutrino. Because ≥ 2.2 -MeV gamma rays can also disintegrate the deuteron, this reaction is very sensitive to radioactive backgrounds. An additional reaction available from supernovae antineutrinos is

$$\bar{\nu}_e + d \rightarrow n + e^+.$$

The SNO collaboration was formed in 1985. P-3's responsibilities include the acquisition of the special PMTs, the on-line data-acquisition system, and the supervision of the research and development tasks for the design and fabrication of the acrylic vessel. The excavation of the

110-ft-deep detector cavity and the adjoining laboratory rooms is complete. By November 1993, the installation of the remaining physical plant and the setup of "class 10,000" cleanroom conditions, which are needed to ensure radioactive cleanliness during the construction of the detector, will be completed. Over 50% of the PMTs have been acquired and tested, and installation began in December 1993. In April 1994, the acrylic vessel will be installed. The detector will be ready to take data in the fall of 1995. We should be able to determine within one year of data taking whether the SNP is due to a flawed solar model or some new property of the neutrino. Regardless of the answer, the observatory will be in operation for at least 10 years.

The use of chlorine to detect the neutral-current interaction is a conservative approach most likely to succeed. However, the need to run with and without chlorine and then compare data sets will result in a 50% duty cycle for neutral-current detection and larger systematic errors. With support from discretionary laboratory funding, P-3 has developed ultralow-background ^3He proportional counters, which may be deployed in the D_2O to detect the free neutron that results from the neutrino disintegration of the deuteron. Backgrounds are further suppressed by pulse-shape discrimination. These detectors are currently being evaluated at a low-background laboratory that P-3 has established at the Waste Isolation Pilot Plant in southern New Mexico.

With these detectors, charged and neutral-current data may be collected simultaneously in SNO, thus greatly improving detector efficiency. Almost 1 km of 5-cm-diam ^3He detectors will be required to instrument the whole D_2O volume. These detectors must contribute no more than one background event per day to the SNO detector. This proposal will undergo funding review. If successful, the SNO detector will be upgraded with these detectors in 1996.

P-Division's Essential Role in the Redirected Inertial Confinement Fusion Program

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During 1990, the National Academy of Sciences (NAS) reviewed the accomplishments, management, goals, and anticipated contributions of the National Defense Inertial Confinement Fusion (ICF) Program. Activities prioritization within the present and future ICF Program were recommended by the NAS and adopted (in large part) by the Department of Energy (DOE). The highest priority is the expeditious demonstration of target ignition and gain in the laboratory. The major portion of the experimental program is being performed initially with the Nova and Precision Nova lasers at the Lawrence Livermore National Laboratory. The intended result of the experiments will be an appropriate technical base that will be used for partial justification of the National Ignition Facility (NIF), a multi-megajoule laser-ignition facility.

As a guide toward a successful program, Los Alamos and Lawrence Livermore National Laboratories have generated, and are well into the execution of, the Nova Technical Contract (NTC), which identifies critical target-physics issues and solution approaches for the indirect-drive concept. Inertially confined fusion targets driven by secondary x-ray sources within a cavity called a hohlraum form the basis of the indirect-drive concept. The NTC is composed of two principal elements: (1) the Hohlraum Plasma Physics (HLP) Program, which addresses all related physics issues within the interior cavity containing the fusion-fuel capsule, and (2) the Hydrodynamically Equivalent Physics (HEP) Program, which addresses physics issues involving the ignition of the fuel capsule. The feasibility of indirect drive requires an energetic and symmetric capsule implosion and experimental results that can be scaled to targets of future interest through theoretical modeling. The target-physics milestones of the NTC must first be met to assess fuel-capsule ignition for NIF target design. To accomplish such an ambitious program within a three- to four-year period, scientists from P-Division Groups P-4, P-14, and P-15 and selected groups from CST Division at Los Alamos are collaborating with scientists at Lawrence Livermore National Laboratory to execute a focused, supportive, and complementary technical effort that continues to yield dividends in the desired areas.

The primary goal of our Drive Symmetry Physics Program is to demonstrate an understanding and control of processes that affect capsule-implosion symmetry. We are investigating the symmetry of implosions by examining the surrounding x-ray drive with two-dimensional x-ray imaging systems developed by P-4 and Lawrence Livermore National Laboratory scientists. From these and similar diagnostics, we have established a technical base of implosion

sensitivities related to important driver parameters, plasma conditions, target fabrication, and hydrodynamics. Figure 12 shows a typical x-ray image of the symmetric implosion of a fusion capsule, as generated by ultra-high-speed x-ray-imaging cameras, designed and implemented by P Division. From the information gathered, we have been able to expand our experimental campaigns at Nova and are now focusing our efforts on time-dependent symmetry effects. As part of this program, Los Alamos scientists also used thin, gold wall hohlraums to obtain x-ray pinhole camera images of both capsule implosions and laser-energy deposition

Fig. 12. This computer-enhanced x-ray image shows an imploding fusion capsule indirectly driven by secondary radiation within a hohlraum.

regions without the use of viewing ports. An example of such an image is shown in Fig. 13. Measurement, understanding, and control of drive symmetry will have direct impact on much of the HEP Program. As such, this program element remains critical in assessing the viability of the indirect-drive concept.

The Hohlraum Plasma Dynamics Program, which is a part of the HLP Program, is now the most critical area with regard to the NTC. Past Nova hohlraum experiments and our recent efforts have called into question our ability to scale results of stimulated-Brillouin-scattering (SBS) and stimulated-Raman-scattering (SRS) reflectivity levels to ignition parameters. The major thrust of our program is the improved measurement of SBS and SRS in long scale-length plasmas relevant to NIF indirect-drive targets. The efficacy of these and other plasma instabilities to produce deleterious effects on the hohlraum energy balance must be quantified and assessed, and the

Fig. 13. A time-integrated image was photographed with an x-ray pinhole camera through a cylindrical hohlraum consisting of a 2- μ m-thick gold wall. The view is normal to the symmetric axis and shows the imploded capsule (center) and the images from the Nova laser beams on each side.

impact of these instabilities to implosions must be established. Low-density foams, which are being developed by Los Alamos target-fabrication experts, may be used to generate long scale-length plasmas for open/closed geometry experiments. These experiments will provide the necessary technical database that will be used with more complex, fully integrated studies. Scientists from P-4 and P-15 continue to conduct experiments on the Nova two- and ten-beam systems and on the new, fully operational 100-J, 50- μm -spot, 100-ps-pulse Trident glass laser at Los Alamos. In a related effort, we are planning to use parametrically generated light for the time-resolved tracking of the associated density gradients. This program element is essential to better understand how plasma physics within the hohlraum affect implosion dynamics.

Our Implosion Hydrodynamics Program, which is a part of the HEP Program, is now being formulated. Cylindrical-target implosions are used to study (within a convergent-geometry framework) critical-fluid instabilities, which may impact our ability to form symmetric implosions. The development of capabilities involving spatial resolution of a few microns and time resolution of a few picoseconds is being developed for the meaningful pursuit of many critical hydrodynamic studies. Scientists from Los Alamos and Lawrence Livermore National Laboratories are now striving to overcome these obstacles by using a combination of ultrafast two-dimensional x-ray imaging and spectroscopic tracers.

A great deal of diagnostic development will be undertaken in the course of our experimental program. Most of the diagnostic development will be driven mainly by the needs of the specific program elements. However, scientists in P-14 have now implemented a unique ion-temperature diagnostic based on a single-hit, neutron time-of-flight (TOF) method. It consists of a 1,020-channel photomultiplier array with 1- to 2-ns time response, coverage of 5×10^7 to 5×10^9 deuterium-deuterium or deuterium-tritium reaction neutrons, and temperature accuracy of 10% or better. Ion temperatures help us ascertain fusion-fuel temperatures by observing TOF spectral changes in fusion neutrons as they travel from the generation points to the photomultiplier detector array located 28 m away. Known as Tion, this diagnostic provides an important capability that will allow us to play a central role in upcoming implosion experiments. Moreover, a full-aperture, beam-sampling system, which is used for measuring SBS when one entire Nova beam is being sampled at full power, will soon be implemented.

The Los Alamos Trident glass laser facility is now fully operational and has had a substantial impact on various aspects of target-physics experiments. The Trident experimental program includes laser development; ICF diagnostic development by Los Alamos scientists, i.e., several new ultrafast x-ray imaging cameras have been produced; ICF Nova experiment staging; ICF diagnostic development by scientists from Lawrence Livermore National Laboratory and Sandia National Laboratories; and weapons-physics experiments, including P-14 and P-15's colliding-plasma study. Scientists from the University of California, Davis, and Imperial College, United Kingdom, are collaborating with us on a number of these experiments.

As an outgrowth of the NAS review process, we feel that a balanced and essential experimental program is evolving. The experiments in this program will answer key questions as to the feasibility of the indirect-drive ICF concept and will play a critical role in the decision process toward the development of the next-generation megajoule-class ICF laser.

Trident Target Physics Program

R. G. Watt (P-4)

We experienced a very productive year at the Trident laser facility at Los Alamos. Target-physics operations started at the end of 1992 with a few target shots per week used for initial focus and intensity tests and diagnostic checkout. Figure 14 shows the target chamber as configured in 1993. Experimental activities expanded over the next few months until the facility was fully operational at midyear. The scheduled target-physics campaigns that followed ranged in duration from a few days to over a month of continual operation for individual experimenters. The

Fig. 14. This configuration of the target chamber at the Trident laser facility in Los Alamos was for the experimental campaigns conducted in 1993.

system ultimately ran 30 to 40 shots per week for Los Alamos ICF and weapons-program users and for external users from the general laser-plasma-interaction community (i.e., Imperial College, London, and Lawrence Livermore National Laboratory). A fairly extensive diagnostic suite has come into operation, including both optical and x-ray streak cameras; time-resolved, x-ray-monitoring spectrometers of the multidiode type; and several variations on the fast (100 ps per image), gated x-ray framing camera, some with spectral dispersion and some with simple imaging optics. In addition, a technique for imaging with a backlighter at energies in the 100- to 200-eV range using reflective multilayer mirrors, yielding 1- to 2- μm resolution, was brought over from Imperial College. This technique was used successfully at the Trident laser facility during a radiation wave-propagation experiment. The facility will add this diagnostic to the available suite in 1994

for users requiring high-resolution, low-energy imaging. In addition, the four-frame, 0.25- μm , holographic-probe imaging system became operational midyear and was used on three different experimental campaigns. By the end of the year, all three beamlines were operational, thus allowing backlighter experiments, pump-probe-stimulated scattering experiments, and a wide range of optical configurations. The flexibility of the system has become a major asset in terms of pulse shape and energy and a variety of optical-illumination geometries.

In addition to using the facility for instrument checkout for three different gated x-ray imagers (two destined for the Nova laser facility at Lawrence Livermore National Laboratory and one for Trident), we ran a number of physics campaigns during 1993 in support of the national ICF program and the Los Alamos weapons-physics program. A beam-phasing campaign aimed at issues relevant to the NIF studied the motion and radiation history of x-rays produced by one drive beam after its interaction with a plasma created by the other beam. The goal of this experiment was to study the control of energy deposition in a situation where the beams may need to propagate through plasmas produced by other drive beams. Early results indicate observable amounts of refractive motion of a beam as it traverses through the plasma caused by another beam, as well as a radiation-power history of each generated plasma correlated with the incident-laser-power history of that plasma. Both elements are important in the calculation of energy balance and symmetry in NIF targets. A detailed comparison of the experiment and

simulation will be used to verify the correctness of our modeling of the laser-plasma interaction upon which the NIF design is based.

Early experiments related to NIF issues were done on SBS. These experiments examined the possibility of SBS occurring at enhanced levels in long scale-length plasmas that result from seeding by sources other than the SBS-generating drive beam itself. Such seeding would have an impact on the final coupling efficiency between the laser and the target in an NIF experiment. Initial results show an enhancement but with large scatter in the data. Further work remains to be done in this campaign to improve statistics and reproducibility.

Two series of colliding-foil experiments were conducted. These experiments examined the collision and stagnation of plasmas generated from the facing surfaces of two plates. Our goal was to understand the dynamics of colliding plasmas and to compare x-ray emission, ion spectra, and possible neutron production with simulations. These colliding plasmas have the potential of generating very high temperatures in the collision region as the directed kinetic energy contained in the blow-off ions thermalizes. Early results suggest ion temperatures in the 100-keV range in the collision region and show evidence, after the drive beams are turned off, of radiation dominated by the collision region rather than the near-plate region, as is the case early in time. We will continue to examine holographic imaging of the collision region and to characterize the temperature of the collision region using the backlighter beam as a probe for Thomson-scattering measurements.

In addition to these ICF and weapons-physics campaigns, several experiments were done in collaboration with personnel from Sandia National Laboratories. These experiments looked at the behavior of foams illuminated by a laser drive beam in an effort to characterize the heating and vaporization process. The ultimate goal was to determine whether foams would make good candidates for creation of long scale-length plasmas for later study or for use in NIF targets. With collaborators from Lawrence Livermore National Laboratory, we examined the propagation of a radial heating wave out from under the laser spot with spectroscopic-imaging techniques. In this series of experiments, an annular structure related to a radial heat wave was seen in x-ray images; this structure will be examined further.

In addition to the experimental campaigns discussed above, external users performed two campaigns that broke new ground in the laser-plasma interaction arena. The ion-wave experiment, now in the characterization phase, is being done with the Institute of Plasma Physics at Lawrence Livermore National Laboratory. This ongoing experiment uses a random-phase plate in the form of strips rather than cells to produce a line focus in each drive beam. The line focus is subsequently split in two and shifted along the line by a two-angle wedge plate (tent plate). The process results in a line focus designed to have two dominant high-intensity regions with a depression of a few tens of percent between them. This focus is used to generate a quasi-steady plasma over a 4-ns time period that is as close to a one-dimensional expansion down the target normal as possible. The plasma generated was characterized in x-ray-emission profiles and with a four-frame, holographic-probe imaging system. The plasma shows completely axial flow in some configurations. The resultant plasma is a testbed for later pump-probe experiments, which will examine the dispersion relation of the SBS spectrum from a long-scale-length plasma (3 mm transverse to the flow direction) in a region of interaction phase space where $k\lambda_{De} \approx 1$, rather than the normally studied region well below 1. New physics involving ion

inhibition of electron thermal conduction and the production of high-energy ion tails can be investigated with this target configuration.

A fairly extensive experiment, conducted in collaboration with Imperial College, London, examined the propagation and structure of heating waves through low-density foams. A recently developed imaging technique, which incorporates an x-ray backlighter source in combination with a high-magnification, low-energy (100 to 200 eV), multilayer-mirror telescope, was used to image the opacity of the foam through which the axial heating wave propagated at spatial resolutions of less than $2\text{ }\mu\text{m}$. This resolution is a factor of 4 better than that achieved at higher x-ray energy using gated x-ray pinhole cameras and is also demonstrably better than that routinely achieved with curved-crystal x-ray telescopes, such as the "22x" at Nova. The energy is high enough to get well past the laser-absorption layer but will not get to as high a density as the typical 2- to 2.5-keV backlighter imaging techniques that have been in use for several years. The technique gives up peak-density range in favor of spatial resolution. In this experiment, imaging was done both in a static mode with a short backlighter pulse (100 ps) and with a long backlighter pulse (in excess of 1 ns) using both gated x-ray imaging and x-ray streak photography. The primary goal of the experiment was to study the effect of preheat x-rays (from a gold foil) on the propagation of an initially nonuniform laser heating beam through the foam target. The propagating heat wave, which had severe nonuniformities in the absence of preheat x-rays, turned into a smooth wavefront when several hundred picoseconds of x-rays preheated the foam before the laser reached it. The most convincing evidence came from low-density foams that were coated with $200\text{ }\text{\AA}$ of gold on the surface upon which the laser was incident; this layer of gold was then subjected to a laser beam. Without the layer of

gold, the wavefront had severe nonuniformities as it propagated inward through the foam. With the gold layer, the wavefront appeared smooth after the laser beam burned through the gold layer and penetrated the foam. An image showing a static, backlit radiograph of a foam target is shown in Fig. 15. Self-emission from the gold region still showed structure. Further work in this area and application of the resulting axial heating wave onto a solid surface with the subsequent observation of Rayleigh-Taylor instability growth will occur in 1994 at the Vulcan laser facility at Rutherford Laboratory in the United Kingdom.

Fig. 15. This image of an x-ray, backlit, low-density foam was taken with a 125-ps x-ray flash. The image shows both the foam opacity and self-emission from a $200\text{ }\text{\AA}$ gold-layer vapor deposited on the laser side of the foam and driven by a low-energy-drive laser beam.

Comparative Studies of Brain Activation with Magnetoencephalography and Functional Magnetic Resonance Imaging

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In the past decade, magnetic resonance imaging (MRI) has become the method of choice for imaging the soft-tissue *anatomy* of the human brain. The past two years have witnessed the emergence of MRI as a methodology for imaging brain *function*. Initial experiments measured blood volume using high-speed, echo-planar imaging techniques to resolve the passage of a paramagnetic material, such as gadolinium, through brain circulation after the chelated element was rapidly injected into a peripheral vein. More recent work has shown that intrinsic physical signals associated with changes in blood volume or in the content of oxygen in the blood can be measured with MRI, thereby eliminating the need for injections of "contrast agents." We recently demonstrated that these types of measurements can be made in standard clinical imagers. Thus, hundreds of existing instruments in hospitals around the world might be usable for functional imaging.

Researchers in the Biophysics Group (P-6) and at the Albuquerque Regional Federal Medical Center (ARFMC) are among the leaders in the development and application of magnetoencephalography (MEG). This technique involves mapping the magnetic fields associated with the tiny currents produced by neural activity. Functional MRI (fMRI) and MEG clearly offer different, and largely complementary, capabilities. We have begun to compare and cross validate the activation maps produced by these techniques. Such studies will allow us to better characterize the relationship between neurophysiological activation and associated hemodynamic changes. A more exciting prospect is the development of analyses that combine information from MEG and fMRI to characterize underlying neural activity with better spatial and temporal resolution than that possible with either technique in isolation.

Our experiments have used both somatomotor and visual neural-activation paradigms. The somatomotor experiments used voluntary flexion of the right hand at a rate of 1 to 4 Hz. Trial blocks of about two minutes were followed by control blocks (without flexion) of the same duration. Visual experiments used a sector of a circular checkerboard pattern confined to a single quadrant of a subject's visual field. Computer-generated images were displayed by video projection. In MEG experiments, a video projector was focused onto a fiber-optic image guide, which was routed into a magnetically shielded chamber where the image was re-projected.

We recorded neuromagnetic activity by using either a 7-channel magnetometer (BTi) at the Los Alamos Neuromagnetism Laboratory or a 37-channel system at the Magnetic Source Imaging (MSI) Facility at the ARFMC. Most experiments involved multiple placements of the sensor array. Data were analyzed by single- or multiple-dipole least squares

fitting procedures. Data will also be analyzed using distributed-current estimation procedures, which are being developed at Los Alamos.

Using a customized gradient echo-image-acquisition paradigm on a Siemens Magnetom 1.5-T clinical imager, we collected 5 or 6 fMRI slices, each of which was 5 to 8 mm thick with a 2-mm in-plane resolution. Parameters involving magnet setup and image acquisition were adjusted for each subject to optimize sensitivity and image contrast. Multiple sets of images were taken during each stimulus or control block, and comparable images were averaged. Difference images were constructed to show the changes between stimulus and control conditions, and statistical tests were performed to assess the significance of the differences.

A strong, early component of the MEG somatomotor response was fit with a single-dipole model, and the calculated source was located within a volumetric anatomical MRI data set (Fig. 16). In experiments to date, agreement between the estimated center of mass of the region of activation disclosed by fMRI and the equivalent current dipole has been reasonable—typically less than 1 cm. The major discrepancy has been along the radial (depth) axis, which may reflect the fact that for the stimuli used the region of activation extends between 1 and 2 cm along the cortical surface.

MEG visual data were analyzed by sampling the response data at 5- or 10-ms intervals and then by fitting the composite, instantaneous field maps with multiple-dipole models that contained increasing numbers of component sources. Appropriate model order (i.e., the number of dipole sources) for each map was determined on the basis of reduced chi-square statistics. Solutions to the instantaneous fits were used as starting estimates for spatial/temporal model fitting. Using this technique, we consistently identified 4 to 6 sources during an 80- to 150-ms poststimulus time interval.

In most of the fMRI data sets (e.g., Fig. 17), the activation of the striate cortex is a dominant feature. In the corresponding neuromagnetic studies, map features associated with V1 activity are typically much less pronounced and thus presumably reflect the increased sensitivity of MEG to source orientation, depth, and the possibility of field cancellation in extended, convoluted sources. fMRI is subject to artifacts from instrument instabilities, blood flow, head movement, and soft-tissue pulsation, among other factors. These possibilities dictate caution about the interpretation of

Fig. 17. Blocks of 6 parasagittal slices, each 5 mm thick, were collected using a T2* weighted acquisition sequence. Visual stimulation consisted of contrast reversal of a pattern—an annular wedge from a circular checkerboard displayed in the lower right visual field. The black and white checks, which made up the checkerboard pattern, reversed at a given frequency. Control periods were interleaved with stimulation epochs. Difference images above a statistical threshold were superimposed on corresponding anatomical images from a volumetric acquisition.

Fig. 16. A t-statistic difference image (upper right) from a multiple slice fMRI exam shows the maximum differences (the light spots, which correspond to regions of neural activation). The anatomical MRI (upper left) corresponds to the difference image described above. The function difference image with a lower threshold at the 99% confidence level is superimposed on the anatomical MRI (lower panel). The diamond indicates the center of mass of the primary activation cluster. The triangle indicates the best fitting MEG-dipole location from a comparable experiment with the same subject.

Fig. 18. The primary visual area that is active from approximately 70- to 100-ms poststimulus was located on orthogonal projections produced from three-dimensional anatomical MRI data (cross hairs on lower panels). The field distribution associated with this source is illustrated in the upper panels. Functional MRI measurements (from Fig. 17) that disclose changes in cerebral blood flow are shown as highlighted overlays on anatomical images in the lower panels.

Fig. 19. Neuromagnetic field measurements of neural sources activated by visual stimulation were analyzed by multiple-dipole, spatial-temporal modeling techniques. Confidence regions determined through Monte Carlo analyses are superimposed on renderings of the head and brain generated from volumetric MRIs for this subject (upper panel). A six (coronal) slice fMRI experiment for a different subject discloses regions activated by visual stimulation (lower panel). Highlighted areas indicate significant differences in the control versus stimulated images.

difference images. Nevertheless, there was generally good agreement between calculated locations of dipole sources and the corresponding regions of activation that were apparent in fMRI difference images (e.g., Fig. 18). Functional MRI also provides evidence of multiple visual processing areas. In the study illustrated in Fig. 19, we have identified regions of activation that correspond to each of the primary sources observed in MEG studies: V1, V2, contralateral, and ipsilateral occipital-parietal sources; an occipital-temporal source; and a source on the ventral surface of occipital cortex. The agreement is surprisingly good, particularly considering that the comparison in this case is across individuals.

Differences in the sensitivity of the techniques and the nature of the underlying physical phenomena dictate different optimal designs for the two classes of experiments. fMRI, which has temporal resolution on the order of seconds based on the time constants of the hemodynamic responses, is most useful for characterizing the location of steady-state activation integrated over time. MEG analyses often exploit the temporal fine structure (millisecond) of dynamic neural-population responses; therefore, the transient presentation of stimuli widely spaced in time is often used. We have shown that it is possible to design stimulation paradigms that produce adequate activation for fMRI while retaining unambiguous temporal information for MEG analyses. However, separately optimizing stimulus rates while preserving more relevant parameters, such as stimulus size, location, and spatial frequency, may be preferable.

MEG and fMRI provide complementary views of neural functional activation elicited by sensory stimulation or voluntary motor control. Clearly, a convergence of evidence from both techniques lends additional credence to observations from either methodology. For example, a number of techniques being developed and tested allow for the reconstruction of distributed, tomographic currents on the basis of MEG data. fMRI provides a useful technique to help validate such methods in applications to real human data.

The development of combined analyses that exploit the strengths of each technique may also prove feasible. fMRI could be used to delimit the locations and spatial extent of regions of activation; the more realistic source geometry provided by MRI should improve MEG model accuracy. Dynamic temporal resolution provided by MEG should allow us to resolve spatially adjacent, functionally distinct areas on the basis of timing differences. Such a composite technique should also allow us to characterize the flow of information through functionally and anatomically distinct processing areas in human sensory and motor systems.

Cellular Communication, Interaction of G-proteins, and Single-Photon Detection

B. M. Willardson, T. Yoshida, J. Wilkins, G. Jensen, B. Thornton, and M. W. Bitensky (P-6)

Genesis: The universe and living cells

The physicist finds compelling evidence for explosive cosmic beginnings in the phenomena of an expanding universe, primordial thermal radiation, and subtle heterogeneities therein. In contrast, the daunting struggles of the biologist to understand the origins of life are fraught with ambiguity, and his tentative scenarios are rife with conjecture. Clearly, the principles of evolution have served as the operative rationale in the design and development of living systems. Life seems to emerge as a single-cell form, enjoying the ambiance of an aqueous milieu. We have no fossil record of how cells initially managed to achieve self-replication, or how they managed to acquire the ability to partition their contents from the surrounding milieu. These remain conspicuous elements in the set of awesome questions that surround the beginnings of life on Earth.

Acquiring information about the milieu and each other

Although little is known about these earliest cells, it is clear that they would have derived considerable benefits from the capability to acquire information about their milieu (where is my food?) and each other (where are my reproductive partners?). If we may judge from the example of their latter-day counterparts (e.g., the free-living amoeba, *D. discoideum*), they had the capability to sense their environment and each other. Moreover, it is highly likely that they used the ancient precursors of modern G-proteins for this purpose (see below).

Multicellular animals

The transition from single- to multicellular organisms launched an era of remarkable cellular specialization and served as an essential prelude to the development of those cellular capabilities that have made possible the spiritual, scientific, sociopolitical, and artistic achievements of our species. Simple diffusion was adequate for sustaining the metabolic activity and for conveying signals to the G-protein-based information systems that were used by single-celled organisms. However, simple diffusion would no longer suffice to feed and inform those deeply embedded cells that are a consistent feature of large multicellular organisms. Two innovations were required as additions to the basic evolutionary plan: (1) a muscular cardiac pump (that is itself regulated by G-protein-mediated signals) for the purpose of circulating and oxygenating the cell's bathing medium and (2) a far-reaching, richly branching nervous system, which is also heavily dependent on G-protein-mediated signal transmission. The cardiac pump allowed animals to internalize and circulate what had been the cell's aqueous

milieu. This innovation permitted cells at some distance from a multicellular organism's surface to receive oxygen, nutrients, and informational molecules. The circulatory system became the internal milieu that eventually would support G-protein-dependent hormonal and immunological signaling. The circulatory system, however, was somewhat encumbered by the limitations of dilution and relative slowness. Thus, a parallel event in the evolutionary plan was the development of more rapidly conducting bioelectrical cables formed by nerve cells (Fig. 20) for orchestrating coordinated efforts by clusters of similar cells such as those found in muscle, liver, or adrenal. Nerve-cell bioelectrical transmission is very rapid (several meters per second), and neurons use G-protein-mediated signal transmission both to initiate and to interpret bioelectrical transmission signals.

Fig. 20. Synaptic function. Heavy arrows show the principal direction of information flow when neurons form a synapse. The "firing" of nerve cells requires an abundance of ATP (the "high-energy" nucleotide that is used to establish ion gradients), and for this purpose, neurons (including rods) maintain a rich complement of mitochondria. The average neuron participates in the formation of about 10,000 synaptic connections and optimizes massively parallel processing.

Neural networks

In multicellular animals, the nervous system emerges as the locus of reason and coordination. Neural networks provide hardware and can acquire software for such diverse functions as problem solving, abstract thinking, locomotion, food location, mate selection, reproduction, predator evasion, and artistic creativity. Nerve cells are arranged in large arrays and networks. Their axons (large cable-like projections for sending signals) bundle together for high-speed signal transmission, and their cell bodies and dendrites (short, highly branched projections for receiving signals) cluster to form neural network arrays that serve as centers for signal processing and analysis. Neural networks are now credited with those pattern-recognition functions that support language use, master's level chess, and the identification of faces. Such functions have been counted among the most challenging frontiers in the emerging world of massively parallel computing. A substantive portion of signaling transactions among nerve cells are heavily dependent upon G-protein-mediated signal transmission. We are studying a very specialized light-sensitive nerve cell (the rod cell) that is used in vision. With the help of G-proteins, the retinal rod cells convert the photon-induced shape change in their rhodopsin molecules into the neurobiological language of neural signaling.

Fig. 21. Anatomy of the rod. The rod is functionally and anatomically divided into inner and outer segments. The outer segment contains about a billion photon-capturing rhodopsin molecules. The inner segment contains the nucleus with its DNA, the mitochondria that synthesize ATP, and the synaptic terminus that is specialized for synapse formation with the retina. The voltage across the rod membrane regulates neurotransmitter release at the synaptic terminus, which makes extensive synaptic connections with its network of retinal neurons.

Rods and cones: Specialized nerve cells

Our experiments focus upon the remarkable properties exhibited by a unique ensemble of signal communication proteins, which are found in the rod and cone cells. The retinal rod cell (Fig. 21) has developed into a widely studied model system of G-protein-mediated signaling. Because its G-proteins are quite similar to those found in a wide variety of cells and signaling processes, the rod effectively illustrates the more general principles of cellular communication. The rods and their companion cells, the cones, are found in the retinas of virtually all vertebrates. These uniquely specialized nerve cells are adapted at one pole for photon capture and at the other for neural transmission. The rod photoreceptor cells function as slower black and white visual sensors that function best in dim light. The cones have evolved as very fast bright-light and color discriminators.

When fully adapted to the dark, the rod cell can function as a true quantum counter that will reliably detect a single photon. Moreover, it can regulate its own sensitivity and function over a wide dynamic range of light intensities. When the dynamic range of the rods is combined with that of the cones, the human retina can respond to a signal intensity range that exceeds 5 orders of magnitude.

Regulation of rod-membrane current

A century has passed since Heinrich Kuhne first observed that the bovine retina, when exposed to light, changes from a rich red purple to a pale yellow. This was the first evidence for a light-induced change in the photon-receptor protein, rhodopsin. By the 1950s, George Wald, Tsuneo Tomita, and their colleagues had demonstrated that a photon-induced shape change occurs in the rhodopsin molecule of rod cells and

that this protein conformational change causes closure of physically discrete, specialized membrane channels in the outer segment of the rod cell. These cation channels support an ion current carried largely by Na^+ (Fig. 22). Ion-channel closure is the event that controls rod-transmembrane electrical potential and thereby transmits a neural signal to the retinal network. A light-regulated rod enzyme called phosphodiesterase (PDE) has the capacity to rapidly degrade the ion-channel-regulating molecule, cyclic GMP (cGMP). In fact, light-induced PDE-driven degradation of cGMP serves as the mechanism for closure of rod ion channels. cGMP is a molecule that maintains the ion channels in their open state, and the enzymatic degradation of cGMP results in ion-channel closure (Fig. 22).

The three-component ensemble of G-protein-mediated signal transduction

G-protein function is characteristically embedded in a three-component ensemble consisting of the receptor, the G-protein, and the read-out protein. In the rod, rhodopsin functions as the signal-receptor protein, the G-protein amplifies and communicates the signal, and PDE functions as the read-out protein. In the "primary" visual event, a rhodopsin (receptor) molecule (containing vitamin A as the photon-capturing moiety) absorbs a photon and consequently assumes an active configuration. The maximum absorption wavelength for this reaction is at 498 nm. This photoactivation step is followed by very rapid interaction of the resulting active configuration of rhodopsin with a large number of rod G-proteins (Fig. 23). Under the auspices of excited rhodopsin, the rod G-proteins bind a cytoplasmic-signaling cofactor, the guanine nucleotide GTP. The G-protein is activated by binding GTP, and the resulting complex can then activate the rod read-out enzyme PDE.

G-protein-mediated signal transmission is used not only for vision but also for smell, taste, hormonal signaling, immunological programming, and nerve-cell transmission.

Fig. 22. Light regulation of rod-membrane current. (a) The Na^+ ion current flows outward from the rod cell body (arrow 1) of the inner segment (IS). A return cation current flows through channels in the outer segment (OS) membrane (arrow 2). (b) The return current is markedly diminished following photon capture, whereas the outward current (arrows) is undiminished resulting in an increase in transmembrane voltage. In consequence, the rod cell sends signals to the retinal net by modifying neurotransmitter release.

Fig. 23. The three-component ensemble of G-protein-mediated signal transduction. The inactive cascade illustrates the molecules that make up the three-component architecture in the absence of signal. A remarkable variety of signals are now identified to use the paradigm of G-protein-dependent signal transduction, including photons, olfactants, hormonal signals, lymphokines (immunological signals), and neurotransmitters (neurological signals). Following signal capture, the activated receptor activates its contiguous G-proteins, allowing them to undergo nucleotide exchange (GTP for GDP) and, in turn, to activate the read-out protein. The G-protein terminates its own activation by enzymatically degrading GTP. In the visual system, one active receptor can activate about 1,000 G-proteins. Moreover, the rapid enzymatic activity of the read-out protein (PDE) further contributes to the gain in signal amplification so that a million cGMP molecules are degraded per absorbed photon.

Cooperative interactions of G-proteins

The inactive (GDP-bound) form of the G-protein has a relatively poor affinity for excited rhodopsin and appears to contribute little in the way of sensitivity or speed toward the process of signal amplification. This initial relatively weak binding affinity may serve to guard against background noise or specious signaling and suggests the need for a compensatory mechanism to provide the sensitivity and amplification needed for single-photon detection.

We have been studying the binding of ^{125}I -labeled rod G-proteins to light-activated rhodopsin and have found that this binding exhibits strong, positive cooperativity. This means that binding of the first G-protein to excited rhodopsin enhances the affinity of the binding of the second G-protein to a second rhodopsin by a factor of 50. This is analogous to the cooperative binding shown by hemoglobin where binding of the first oxygen to one of the hemoglobin subunits enhances binding of subsequent oxygen to other subunits. In the case of the vision G-proteins, this mechanism of positively cooperative binding appears to depend upon formation of a dimer between the excited rhodopsin and a second (possibly nonexcited) rhodopsin. It is the second rhodopsin that appears to form the high-affinity, G-protein binding site. This cooperative binding is an attractive candidate to explain the rapid and spectacular amplification of photon signals by rods, e.g., a single photon can orchestrate the enzymatic degradation of a million channel-opening cGMP molecules. Such signal amplification is essential for rods to

operate at very low photon-flux densities. The possibility that the $(\text{rhodopsin})_2$ -G-protein complex could serve as a matrix that generates large numbers of active G-proteins at a second high-affinity site is now being studied (Fig. 24). In this hypothetical scenario, the first G-protein—receptor complex remains intact, and rapid serial formation of many activators is engendered at the second high-affinity G-protein binding site. Such an arrangement could provide the rod with the low-noise and high-sensitivity features that permit single-photon detection.

Integrating rod physiology and biochemistry

Living cells and especially nerve cells such as the rod have been studied traditionally from two perspectives: (1) the intact rod cell can be isolated, and its membrane current responses to pulses of light can be accurately measured, and (2) since the early 1970s, many laboratories have been attempting to elucidate the fine details of the interactions of rod signaling-protein ensembles, which support the downstream consequences of photon capture. Now, the challenge is to explain whole-cell electrophysiological events in terms of the integrated functions of rod signaling-protein ensembles that are, in fact, the “behind-the-scene” biochemical players that shape the electrophysiological features of the photo response.

Fig. 24. Positive cooperativity. An active G-protein is generated at a second, positively cooperative, high-affinity binding site. The G-protein binds to the second site (R_2) with an affinity that is about 50 times greater than that exhibited by G-protein binding to the first site (R_1). Because one photon can cause the activation of more than 1,000 G-proteins, we are attracted to the possibility that high-speed G-protein activation is carried out at R_2 . The rod G-protein is a heterotrimer. It is the α subunit that exhibits the capacity to bind GTP in place of GDP under the auspices of active rhodopsin, and as the complex $G\alpha$ -GTP, it has the capacity to cause activation of PDE.

Nuclear Magnetic Resonance Studies of Oxygen-doped $\text{La}_2\text{CuO}_{4+\delta}$

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Both the normal and superconducting states of high- T_c cuprates are unusual, and their properties remain poorly understood. One important aspect is the structure of the cuprates, which interestingly varies on local scales. Also evident is the tendency of mobile carriers in the cuprates to separate into regions of high and low density. To maintain charge neutrality, regions that contain a high density of (positively charged) mobile carriers also contain a larger density of (negatively charged) oxygen ions. Thus, the phase separation of holes is accompanied by the formation of regions of high and low excess oxygen density. In contrast to the highly mobile excess oxygen ions, other cations are immobile, so this separation can only occur on a very local distance scale because macroscopic phase separation is thwarted by long-range Coulomb forces that make the clumping of charge energetically unfavorable. We have studied La_2CuO_4 doped by the addition of excess oxygen (a good high- T_c superconductor with T_c as high as 45 K) to gain insight into the relationships between local structure and the behavior of mobile carriers.

Because the oxygen dopants in $\text{La}_2\text{CuO}_{4+\delta}$ have very high mobility in contrast to metal cation dopants, macroscopic phase separation is possible. Using nuclear-magnetic-resonance (NMR) techniques, we can

Fig. 25. Phase separation is shown in $\text{La}_2\text{CuO}_{4+\delta}$. The temperature is plotted against the excess oxygen content δ . Note that δ is independent of temperature below 235 K for the low-hole-density phase and 200 K for the metallic high-hole-density phase. Note also the very abrupt change in δ for both phases.

determine the temperature dependence of the excess oxygen concentration in both phases: (1) a low-hole-density phase and (2) a high-hole-density phase (Fig. 25). The diagram has some unusual features. First, the excess oxygen content δ changes very abruptly for both phases. Moreover, the sides of the diagram are vertical below about 200 K. We have used relaxation measurements of the nuclear spin lattice in ^{139}La to probe the motion of oxygen atoms. A strong ^{139}La relaxation peak at 210 K in $\text{La}_2\text{CuO}_{4+\delta}$ indicates the temperature where the characteristic frequency for oxygen motion [which decreases as $\exp(-U/k_B T)$, where U is between 0.7 eV and 1.4 eV] equals the Larmor frequency (i.e., a very low frequency of about 50 MHz). This evidence for the loss of oxygen motion indicates that the vertical sides of the phase diagram are due to the loss of oxygen mobility.

These results suggest that structural effects may play a role in driving phase separation. In addition, the fact that the

superconducting transition temperature T_c in oxygen-doped $\text{La}_2\text{CuO}_{4+\delta}$ can be increased by slow cooling indicates that achieving an optimum local structure may be important for enhancing T_c . Our studies of the temperature regimes and cooling rates, which are important for increasing T_c , have shown that T_c increases steadily with decreasing annealing temperature from room temperature down to 200 K. Annealing below this temperature results in the same T_c that is achieved after rapid cooling from room temperature. Although the exact relation to phase separation is not understood, the weak dependence of T_c on annealing temperature shows that this cannot be simply explained as a result of incomplete phase separation. These studies support the view that optimum structure, which can only be achieved by annealing, is essential in achieving the highest T_c .

The primary focus of our work has been to gain a detailed understanding of local structure in $\text{La}_2\text{CuO}_{4+\delta}$. The quadrupole shift of the ^{139}La NMR frequency is a very sensitive local probe of the lateral displacement of the apex oxygen and thus of the structure of the La-O layer. We have found that the structure of $\text{La}_2\text{CuO}_{4+\delta}$ is very sensitive to the presence of doped holes. In contrast to undoped La_2CuO_4 ($\delta \approx 0$), which displays a nonzero, well-defined lateral displacement of this oxygen, the apex oxygen in metallic $\text{La}_2\text{CuO}_{4+\delta}$ is not displaced at temperatures above T_{PS} . More importantly, a distribution of lateral displacements develops upon cooling below T_{PS} (Fig. 26). This distribution is not a manifestation of the distortion surrounding an interstitial dopant but rather the response of the crystal to the presence of doped holes.

We have employed copper nuclear-quadrupole-resonance (NQR) spectroscopy as a local probe of electric field gradients in the CuO_2 planes. In $\text{La}_2\text{CuO}_{4+\delta}$, we have shown the existence of a second, distinct copper site that cannot be explained by crystallographic results. Comparison of these results with data from $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ allows us to show that the second site is differentiated not by the presence of the dopant but by a feature common to both materials: the presence of doped holes. Again, undoped La_2CuO_4 displays only a single, copper NQR line.

Our studies of the multifaceted behavior of oxygen-doped $\text{La}_2\text{CuO}_{4+\delta}$ have provided important insight into the interactions between mobile carriers and local structure. The fact that these appear to be unusually strong in the high- T_c cuprates suggests important avenues of study for furthering our understanding of this unusual and important phenomenon.

Fig. 26. The distribution of lateral oxygen displacements is indicated by the tilt angle θ of the La-O bond away from the crystalline c -axis ($\mu = \cos \theta$). Tilting begins to develop at the temperature T_{PS} ; tilting increases as the temperature continues to decrease. At low temperatures the distribution of μ is nearly uniform up to the cut-off value.

Thermoacoustic Engines

G. W. Swift, J. Olson (P-10, now MST-10), W. C. Ward (ESA-13), and R. Radebaugh (National Institute of Standards and Technology)

A sound wave is usually thought to consist of coupled pressure and velocity oscillations, but an adiabatic temperature oscillation always accompanies the pressure oscillation. The temperature oscillation is usually unimportant except as it contributes to the attenuation of sound in bulk and at boundaries. However, under some circumstances, the temperature oscillation and, in particular, its interactions with boundaries, known as thermoacoustic effects, can be harnessed to produce powerful, useful thermodynamic effects.

Both of the two basic types of heat engines can be realized thermoacoustically: (1) in a thermoacoustic prime mover, heat flow from higher to lower temperatures produces work in the form of acoustic power, and (2) in a thermoacoustic heat pump, acoustic power is used to pump heat from lower to higher temperatures. Whereas typical heat engines have crankshaft-coupled pistons or rotating turbines, thermoacoustic engines have no moving parts or, at most, a single flexing part (such as a loudspeaker) with no sliding seals.

The earliest thermoacoustic engine was the Sondhauss tube. Over 100 years ago, glassblowers found that when a small, hot glass bulb was being blown on a cool glass tubular stem, the stem tip sometimes radiated sound. Scientists made steady progress understanding such phenomena, but it was not until the 1980s in the Condensed Matter and Thermal Physics Group (P-10, now MST-10) that we learned how to design powerful thermoacoustic engines with efficiencies between 10% and 30% of the maximum possible efficiency—that is, the Carnot efficiency—allowed by the first and second laws of thermodynamics. Thanks largely to our work and subsequent evangelism, about two dozen researchers worldwide are now studying various fundamental aspects of thermoacoustics and developing applications ranging from sonar projectors to freezers for the space shuttle.

One application we are pursuing in MST-10 is the use of thermoacoustics to liquefy natural gas by using the combustion of natural gas as the power source. This proposed work is in collaboration with the National Institute of Standards and Technology in Boulder, Colorado. TANGL (ThermoAcoustic Natural Gas Liquefier) will have absolutely no moving parts and require no electrical power. In short, our invention uses acoustic phenomena to produce refrigeration from heat with no moving parts. The required apparatus comprises nothing more than heat exchangers and pipes (made of common materials) without exacting tolerances. It will be highly efficient and remarkably reliable at low cost. Fig. 27a shows our present idea of how a large TANGL might look.

Natural gas currently provides one-quarter of America's energy supply, and domestic gas reserves will outlast oil reserves by many decades at current levels of consumption. Although most natural gas is still carried from well to user as gas in pipelines, the use of liquefied natural gas has been increasing 10% to 15% per year. The large liquefaction plants and cryogenic storage tanks that exist throughout the United States are close to major consumption centers for seasonal peakshaving, handling about one-third of the total gas supply. In seasonal peakshaving, a relatively constant flow of gas through pipelines

from the gas fields to load centers can be maintained throughout the year by liquefying and storing the excess flow when demand is low in the summer and by vaporizing it as needed when demand increases in the winter. Ocean transport vessels of 100,000-m³ capacity are also commonplace, as are attendant coastal liquefaction and storage facilities.

TANGL will be maintenance free, inexpensive, portable, and environmentally benign. It will enable economic recovery of natural gas from wells that are too remote to justify the construction of a gas pipeline, thus increasing the domestic gas supply by 6%. TANGL could also be used in offshore gas recovery from sites inaccessible to pipelines, in small-scale recovery of methane from organic waste, in recovery of natural gas entrained in petroleum, and in local liquefaction of natural gas for a variety of purposes. We expect that our first large TANGL will liquefy 70% of its throughput by burning the remaining 30%. We also expect further research to lead to increased efficiency.

Figs. 27b and 27c illustrate in detail the operation of one portion of TANGL—that is, the conversion of heat to acoustic power in the thermoacoustic engine. Basically, the acoustic power is generated by oscillatory thermal expansion and contraction of the helium gas in the engine. The oscillatory thermal expansion and contraction process is in turn due to the acoustic motion of the gas along the temperature gradient in the engine. The standing wave of the resonator carries the parcel of gas shown back and forth, compressing and expanding it, with phasing such that the parcel is at its most compressed state when it is at its farthest right position. The presence of the solid engine parts with their steep temperature gradient adds an important element to this otherwise simple acoustic oscillation—oscillatory heat transfer between the parcel of gas and the solid. When the parcel is at its rightmost position, heat flows from the relatively hot solid into the parcel, thereby expanding it. When the parcel is at its leftmost position, heat flows from the parcel to the relatively cool solid, thereby contracting the parcel. Because expansion takes place at the high-pressure phase of the cycle and contraction takes place at the low-pressure phase of the cycle, the parcel does net work on its surroundings. This net work generates the sound that maintains the resonance and provides power to the refrigerator portions of the system. Remarkably, the thermoacoustic conversion of heat to acoustic power just described can take place with an efficiency as high as one-third of the maximum efficiency allowed by the first and second laws of thermodynamics.

Fig. 27. (a) The large TANGL shown here will be capable of handling the entire output of a small well. The TANGL that we propose to build first will have 2% of the capacity (and 2% of the volume) of this large one. (b) The magnified internal view of part of the thermoacoustic stack shown here illustrates the conversion of heat to acoustic power by one small parcel of gas. (c) The thermodynamic cycle followed by the parcel of gas in Fig. 27b is shown here.

Over the course of several years, we have sharpened our ability to compute the performance of any thermoacoustic apparatus from its geometry and gas properties. This year, in collaboration with Bill Ward in ESA-13, we have distilled all our current knowledge of thermoacoustics into a user-friendly computer code that we will soon release to the public. The code accepts input files describing the geometry (as well as the gas and solids used) of acoustic or thermoacoustic devices of nearly arbitrary complexity and computes every measure of performance that we have ever found useful. We have successfully tested it against experimental data taken at Los Alamos and elsewhere. The initial response of outside users who have tested the code for us has been extremely enthusiastic.

This code is based in part on the assumption that the amplitudes of all quantities that oscillate at the acoustic frequency (e.g., pressure and temperature) are small compared with their mean values. But we are starting to build and test systems with amplitudes of 10% to 20% of mean values; our predictions are then off by typically 10% to 60% because of nonlinear effects such as turbulence and streaming. As a first step toward understanding such effects, we have derived the dimensionless groups of variables relevant to thermoacoustics so that we can at least correlate the behavior we don't understand. And as in aerodynamics where knowledge of the relevant dimensionless groups enables meaningful wind-tunnel testing using scale models, we have found that meaningful thermoacoustic scale models can be made. For example, one can use argon with a one-third scale model to test a full-size design that would operate with helium; this scaling law will significantly simplify the development of TANGL. As a second example, a model operating at modest temperatures with low-pressure gas can be used to test a design intended to operate at higher temperatures and pressures. One such use of this type of scaling would be to model a satellite-based engine for producing electricity from a radioisotope heat source. In typical radioisotope-powered satellite equipment, both the heat-source temperature (typically in the refractory-metal range) and the heat-rejection temperature (typically for above room temperature) are too high for the convenient testing of early prototypes in a laboratory.

A Shipborne Raman Water-Vapor Lidar for the Central Pacific Experiment

P. R. Forman (P-14), M. V. Hynes (NW), and the CEPEX Lidar Team

On January 6, 1993, our lidar (LIght Detection And Ranging) group was presented the opportunity of joining the Central Pacific Experiment (CEPEX) to conduct climatological studies using a Raman water-vapor lidar onboard the research vessel, the John Vickers. Two serious obstacles, however, blocked this plan: (1) the fact that Los Alamos did not have a Raman water-vapor lidar suitable for onboard operation, and (2)

The Los Alamos lidar CEPEX team was awarded a Large Team Distinguished Performance Award for their high-resolution measurements of two-dimensional water vapor profiles over the central Pacific Ocean. Members of the team, from left to right, include C. R. Quick, Jr., D. I. Cooper, W. Cottingham, W. E. Eichinger, L. L. Tellier (bottom row); P. C. LaDelfe, B. F. Busse, C. J. Clinton, M. A. Chavez, K. B. Pfeufer, J. J. Tiee (second row); M. V. Hynes, D. A. Poling, C. R. Odom, J. M. Lewis, C. F. Keller, Jr., P. R. Forman (third row); J. A. Wells, J. R. Griego, L. D. Smith, C. F. Lebeda, R. G. Thornton (fourth row).

the John Vickers was at sea on a research campaign known as TOGA-COARE. It would only dock in Honiara, Guadalcanal (Solomon Islands) for a few days in May. The last day for final onboard testing was March 7, 1993. This was very reminiscent of the situation that Los Alamos faced with the "Christmas Lidar" just before Desert Storm: very little time, a firm deadline, and no equipment but sufficient "in-house" experience. Bolstered by our Desert Storm experience, we therefore initiated the CEPEX lidar program.

The aim of the CEPEX project was to acquire sufficient data to judge the validity of a hypothesis concerning the warm pool of the central Pacific Ocean, which apparently never seems to get above 305 K. Members of the Scripps Institute of Oceanography proposed that the high cirrus clouds that form when the surface temperature approaches 305 K act as reflectors of the sunlight and constitute a type of thermostat for the region. An international team of scientists was assembled, and a research campaign was planned to document conditions in this region. Modeling this region required data on the location and optical thickness of cirrus clouds. In addition, a knowledge of

the distribution with altitude of the most important greenhouse gas, water vapor, was critical.

At the heart of our experiment is a pulsed, ultraviolet excimer laser, which was purchased specifically for CEPEX. This particular laser can be operated at 200 Hz with an average power output of up to 60 W in a string of 20-ns pulses. Two wavelengths are possible: 248 nm or 351 nm. The unit operates more efficiently at the 351-nm wavelength. However, sunlight interferes with data collection; therefore, we operate the unit at the 351-nm wavelength only at night and at the 248-nm wavelength during the day. This task is accomplished by switching from XeF to KrF

as the working gas. The laser light is directed upward. As it strikes molecules and aerosols in the air, light is scattered back toward the laser. This scattered light is collected by a 24-in. telescope and directed toward photomultipliers.

We collected three channels of data: aerosols, water vapor, and nitrogen. Aerosols, which give the strongest signal, scatter off particulates in the air, yielding signals with no change in wavelength. For the aerosol channel, a small portion of the returning light (4%) was separated out by a beam splitter. The other two channels, nitrogen and water vapor, have characteristic wavelength shifts. The Stokes line, which is associated with the first vibrational state of the molecule involved, gives a sufficient shift to allow it to be conveniently distinguished by using optical filters. Because we could easily determine the amount and distribution of nitrogen, it was used to normalize the water-vapor data so that only relative calibrations were required; unfolding the lidar equation is not necessary. The outgoing laser beam and the telescope shared a common mirror, which was under computer control to compensate for the roll of the ship. The return signals from the scattered light were digitized, or photon counted, and the information was stored on optical disks.

Data were taken as the ship traveled eastward at a latitude of 2° S parallel to the equator from 158° E (Guadalcanal) to 173° W (Christmas Island). By averaging the data for several minutes, we obtained profiles of the water vapor as a function of height. The maximum height was about 3.5 km for daytime operation and 10 km for nighttime. Fig. 28 is a typical plot of the reduced data. For comparison, the smoothed data from a conventional balloon sonde released from the ship are shown. The balloon data were taken over a period of hours and were affected by the wind as it deflected the balloon's path. Because the path taken by lidar's laser is vertical and we were able to collect data in a matter of minutes, exact agreement is not expected. Data from the balloons could only be collected every 12 hours when the balloons were released, whereas lidar data were collected almost continuously.

The CEPEX lidar was supported by the GEONET (Ground-based Earth Observing NETWORK) Program as part of an effort to keep nuclear-weapons test teams together during any moratorium on underground nuclear test shots. Building and fielding this experiment on an extremely short timescale involved a cast of hundreds. People from MAT, J, P, CLS, SST, WX, X, and MEE Divisions and from EG&G Energy Measurements, Inc., and Johnson Control, Inc., participated. The sincere interest and cooperation of all are greatly appreciated and were essential for the successful completion of the CEPEX research.

Fig. 28. A comparison of sonde and lidar water concentrations on March 11, 1993, 0657 GMT, is shown.

Angara-5 Pinch Temperature Verification with Time-resolved Spectroscopy

G. Idzorek (P-14) and R. G. Hockaday (P-4)

Early in the spring of 1993, scientists from Los Alamos, Sandia, and Lawrence Livermore National Laboratories prepared for a mission to a Russian weapons laboratory. Ten years ago, this scenario would be found only in spy thrillers. However, with the breakup of the Soviet Union, scientists from these three major United States weapons laboratories traveled openly as invited guests of the Russian government.

After the Soviet Union collapsed, scientists at the once secret Russian pulsed-power laboratory, Angara-5, which is located at the Trinit Laboratory 38 km from Moscow, were left with indications that remarkably high implosion temperatures had been achieved in their machine, but they did not have the technological or financial resources to confirm these indications. Scientists involved with Sandia's pulsed-power

machine, Saturn, were intrigued by the rumors of the Russian achievements and proposed a collaboration between the United States and Russian laboratories. The United States would install sophisticated x-ray diagnostic equipment on Angara-5 to either verify or disprove Russian claims of the machine's performance. The expertise to measure and model nanosecond x-ray events resided at the United States weapons laboratories. Thus Sandia invited scientists from Los Alamos and Livermore to participate in a series of Angara-5 experiments scheduled for the summer of 1993.

Physicists from the Fast Transient Plasma Measurements Group (P-14) at Los Alamos fielded an x-ray transmission-grating spectrometer (TGS), which provides spectral- and time-resolved x-ray data from 60 eV to 2 keV with a 1-ns time resolution. TGS data were acquired and stored with a streak camera system operated by personnel from EG&G Energy Measurements, Inc. Sandia and Livermore fielded x-ray imaging and spectral diagnostics, as well as current-flow diagnostics. While the DOE and the Russians worked out the political details of the collaboration, the P-14 physicists adapted their spectrometer to operate in Russia because electrical power, compressed gas, bolt standards, cables, and language (even the alphabet) are different between the two countries. At the beginning of May 1993, Los Alamos and EG&G shipped 3,000 lb of equipment (including a spectrometer, a streak camera, and adapters) and other supplies to Russia. Two teams from Los Alamos each spent three weeks at Angara-5 with a one-week overlap. The first Los Alamos team shipped out to Moscow on May 22, 1993, to receive and assemble the TGS experiment, and the second team shipped out June 9, 1993. The prestaging efforts

Joe Gonzales (left, kneeling), Sonny Gallegos, Bob Hockaday, and George Idzorek are the Los Alamos team members who installed an x-ray transmission grating spectrometer on Angara-5 in Troitsk, Russia, to verify Russian claims of the machine's performance. This sophisticated x-ray diagnostic equipment provides spectral- and time-resolved x-ray data from 60 eV to 2 keV with a 1-ns time resolution. The spectrometer (to the left of Joe Gonzales) is on top of the Angara-5 machine.

of Los Alamos and Sandia allowed for easy TGS and other diagnostic installations, and experiments began June 1, 1993. A total of 31 shots were fired on Angara-5 between June 1 and June 23.

The Angara-5 machine consists of eight pulse lines arrayed symmetrically around a cylindrical load. When Angara-5 is triggered, 2-MV pulses arrive simultaneously at the cylindrical load and create a large 4-MA peak current flow in the load. The large current generates a magnetic field and vaporizes the load. The interaction of the magnetic field and the current drives the vaporized load inward toward the axis. The imploding load stagnates when it reaches the axis. Its kinetic energy is then converted into heat. If the eight pulse lines fire perfectly and the load implodes symmetrically, tremendous temperatures are generated. A typical Angara-5 implosion will reach temperatures of 70 to 80 eV (about 1.5 million degrees Fahrenheit) for a few nanoseconds. At these temperatures, the plasma generates most of its radiation in the form of soft x-rays.

The TGS uses an x-ray transmission diffraction grating to disperse the plasma radiation in energy. The energy-dispersed plasma radiation creates photoelectrons on a gold-coated, microchannel-plate amplifier. The exiting microchannel-plate electrons are then line focused onto a cadmium sulfide phosphor, which converts them to a light signal. The light is coupled through multiple fiber-optic cables to streak cameras. The line source is then streaked in time to provide a two-dimensional picture of energy versus time—the light intensity is proportional to the x-ray intensity at a given energy. The resulting image is digitized and stored on a portable computer system.

An analysis program at Los Alamos unfolds the photocathode calibration, camera distortion, higher-order diffraction contributions, and fiber-optic-link efficiency from the digitized data to create a picture of energy versus time versus x-ray intensity. The energy spectrum at a given time can then be compared with calculated spectra of sources at given temperatures to obtain a measurement of the implosion temperature at that time. The preliminary spectrum, which was assembled from the two streak cameras (Figs. 29 and 30), is from a slice in time at maximum signal output. In Fig. 29, the entire unfolded spectrum shows some statistical scatter from the merging of the two interwoven streak-camera images. At the lower photon energies, there are large uncertainties resulting from the subtraction of the large, second-order light contributions. The high-energy side of the spectrum may be showing electronic or spectral bleed over. Thus, the region of greatest confidence in Fig. 30 is displayed with a range of Planckian curves used to bracket the temperature. This set of curves apparently shows that the spectrum is not a perfect match to a Planckian source. The inferred temperatures for this

Fig. 29. The preliminary peak-signal, time-resolved spectrum is from the Angara-5 Shot No. 2617.

Fig. 30. The preliminary peak-signal, time-resolved spectrum (Shot No. 2617) is displayed over the range of greatest confidence with a range of Planckian curves.

shot can be bracketed between 70 eV and 90 eV, and if we use the dominant portions of the data at about 180 eV and above 500 eV, the inferred spectrum is approximately 85 eV.

So, the big question: Did the Russians achieve a 140-eV implosion temperature? Our answer: The source temperature is about 85 eV, which is about 7 times less energy output than the Russian's recorded. Apparently the Russian x-ray diodes used to measure the high temperature had poorly known responses that were caused by x-ray absorption edge effects. These effects, when coupled with a lack of redundant high-speed measurements, gave the illusion of much higher temperatures than we would have expected. However, the speed of the implosion process surprised us. The rise time of the x-ray signal was so fast that it outstripped Sandia's 400-MHz bandwidth recording capabilities. After further analysis of the Angara-5 data, Sandia will modify the implosion experiments at the Saturn Facility. The results from these Saturn experiments will then be used to plan a return trip to Angara-5 in 1994.

Russian Collaborations on Megagauss Magnetic Fields and Pulsed-Power Applications

L. R. Veaser, C. A. Ekdahl, Jr., P. J. Rodriguez (P-14), and Collaborators from DX-Division, X-Division, and the Nuclear Weapons Program Office

The energy density in a 10-MG magnetic field is around 60 times that of a detonating high explosive. In this state, the magnetic field strongly resists confinement. The field heats and blows apart surrounding equipment, and in this process, electromagnetic noise is emitted. Although these extreme conditions are, of course, difficult to produce, obtaining them makes a number of very interesting activities possible. The energy can be dumped into a load with a significant impedance, such as a cylindrical foil "liner," which then implodes and generates intense x-rays. Alternatively, the magnetic field can compress metal adiabatically to reach unexplored states of matter, or the magnetic field can be used to study the physics of highly magnetized materials.

Although fields of a megagauss or more can be generated by switching the current from a large capacitor bank into a suitably designed load, larger magnetic fields are normally produced by compressing the field into a smaller volume using high explosives. In this process, the chemical energy of the explosives ends up concentrated in the magnetic field. The same process can be used to generate huge electrical pulses and intensely concentrated magnetic energy.

At Los Alamos, research in the use of high explosives to compress magnetic fields has been going on since the early 1950s. Not until 1979, however, at the time of the Second Megagauss Conference in Washington, D.C., did we learn of the extensive simultaneous work in the Soviet Union by A. I. Pavlovskii, V. K. Chernyshev, and their groups. Ten years later, at the Megagauss-V Conference in Novosibirsk, Russia, Pavlovskii and Chernyshev reported several remarkable advances in flux-compression technology. These advances included reproducible magnetic fields of 10 to 17 MG, pulsed currents of 250 MA, and stored energies of 100 MJ. (In the United States, we have stored about 50 MJ of energy and produced 150-MA currents. Our largest fields are similar in magnitude but are not reproducible from shot to shot because the sensing probes are often damaged before compression is complete.) It became apparent that the Russians had concentrated their resources, including scientists hand picked by A. Sakharov, into this area to make it a model of their scientific accomplishments. Their achievements provide previously unknown possibilities for accessing extreme states of matter in the realm of "high-energy-density physics." Their work is actively under study at Los Alamos, mostly by the X and DX Divisions. (Interestingly, the prime motivation for the Russian efforts was the publication in about 1960 of Los Alamos' accomplishments in this area.)

The collapse of the Soviet Union and the Russian economy led to United States concern about a "brain drain," or the emigration of Soviet nuclear-weapons personnel to non-nuclear countries. In response, the United States encouraged interactions between Los Alamos and the Russian nuclear-design laboratories. In exchange visits in early 1992, Laboratory Directors from Los Alamos and from Russia's premier

nuclear-design laboratory, the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF), identified megagauss technology as appropriate for joint work. Los Alamos was able to respond quickly to this emerging national policy because of our previous professional contacts and our past work in this area. In particular, P-14 has done diagnostics and measurements on large magnetic-flux compression experiments for over a decade. Under the leadership of Stephen Younger, the Deputy Program Director for Nuclear Weapons Technology at Los Alamos, we are participating with personnel from X and DX Divisions in collaboration with the Pavlovskii and Chernyshev groups from VNIIEF.

The existence of VNIIEF, the facility where the first Soviet nuclear weapons were developed, was not acknowledged until 1990. It is located in the town of Sarova (designated Arzamas-16) about 300 miles east of Moscow. The laboratory, which employs about 25,000 people in a city with a population of 100,000, combines the functions of Los Alamos, Sandia National Laboratories, and the measurement groups from EG&G Energy Measurements, Inc.

In a series of planning meetings, we outlined some potential collaborative experiments, and in 1993 we executed two of them. The first, in September 1993 at VNIIEF, used one of Chernyshev's disk-explosive, magnetic-flux-compression generators to deposit 35 MA of current and 3 to 4 MJ of energy into an aluminum liner to implode it at 50 km/s. Disk generators have been largely overlooked in the United States in favor of cylindrical generators that are detonated on a line along the axis. Disks are also cylindrical, but the explosives are detonated at several points on the center line. They are modular and can be scaled to large sizes, and they do not require the advanced line initiator.

The experiment at Arzamas featured extensive VNIIEF and Los Alamos diagnostics, detailed comparisons of preshot calculations by both teams, and gave us our first look at the disk generator and at the engineering drawings of both the generator and its advanced high-current foil opening switch. P-14 took high-speed, fiber-optic sensor and recording equipment to Russia to measure the output current from the flux-compression generator and the input to the liner. Our fiber-optic sensors have features that are apparently new to the Russians; in turn, we learned about their diagnostics and their advanced flux-compression methods. Although we have occasionally measured higher total currents, the switching rate of current from the generator into the load was faster than Los Alamos has ever achieved and required our state-of-the-art diagnostics.

The second joint experiment was conducted during November and December at Los Alamos. This experiment involved a series of five high-magnetic-field measurements. Los Alamos explosives imploded MC-1 compression generators built at VNIIEF by Pavlovskii's group to attain fields up to 11 MG (Fig. 37).

Pavlovskii's generators are staged to reduce the effects of instabilities in achieving high compression. A high-explosive charge on the MC-1 is detonated uniformly around the outer surface. When the detonation reaches the inner surface of the explosive, it

Fig. 37. The light material in the front of the Russian MC-1 generator is a mockup of the high explosive, which will be ignited on the outer ten-sided radial surface. The protruding cylinder in the center is the first cascade stage. It comprises 5,000 tiny, toroidally wound wires epoxied together. These wires connect two flanges at the back. A second, small-diameter cascade stage containing the diagnostics is held in the center. Electrical cables from the capacitor bank feed into flanges to provide the seed current in the first cascade. The flange shown at the far end clamps the cable shields while the cable center conductors feed through the small holes to an inner flange adjacent to the explosive.

crushes the thousands of tiny wires that form the first cascade stage. An axial magnetic field, which is formed by current flowing from a capacitor bank through the wires, fills the inside of the first stage. When crushed, the wires short together, trapping the magnetic flux inside. As the first stage implodes toward the axis, the magnetic field is compressed into the resulting smaller volume. A second cascade stage, not shown in Fig. 37, has a diameter about 20% as large as the first stage and is positioned at the center. The magnetic flux initially penetrates the wires of the second cascade, but they also short together and are driven inward when the first cascade strikes the second cascade. At that point, the magnetic flux is trapped inside the second stage, allowing further compression. This staging process reduces instabilities by transferring momentum to the second stage, which is cold and solid, just as the first stage is beginning to disassemble.

Inside the second cascade, we fielded a low-density, plastic-foam cylinder containing diagnostic sensors on its axis. The diagnostics measured the record magnetic fields. In addition, we observed microwave transmissions through high-temperature superconductor samples held at low temperatures to determine the magnetic-field values at which they become normally conducting, and we measured high-field nonlinearities in the Faraday effect for 543-nm laser light in a cadmium sulfide crystal.

It is hoped that collaborations with the two groups from the VNIIEF will continue at a rate of about two experiments per year with each group alternating between Arzamas and Los Alamos. The extensive list of potential experiments includes a 100-MJ flux-compression experiment with a fast opening switch, a 1- to 2-MJ soft x-ray generator, the isentropic compression of a metal to a 10-Mbar pressure, the design and testing of a 20-MG magnetic-field experiment, the formation of a high-temperature plasma, and a proof test of Los Alamos' planned 36-MJ Atlas capacitor bank. New ideas for collaboration are continually emerging as the two teams become more familiar with each other's capabilities and areas of expertise.

Russian technology is expected to play a major role in the Los Alamos AGEX II research program. By collaborating with the Russians, we hope to save many millions of dollars in research money that would be needed to reproduce and understand their successes. Moreover, we are progressing much faster in our understanding of the principles involved in high energy density than we would have on our own.

We have moved cautiously in establishing our relationship with VNIIEF. At each step, we have kept Laboratory and DOE officials informed; in return, they have encouraged us to continue to expand our interactions. Other United States agencies, including the Department of Defense, the National Science Foundation, the United States Air Force, and the Defense Nuclear Agency, are monitoring our progress in anticipation of finding ways to incorporate Russian technology into their own programs through similar collaborations.

Studies of Energy Coupling from Underground Explosions

R. E. Hill and B. L. Wright (P-15)

The 1974 treaty between the United States and the Soviet Union on the Limitation of Underground Nuclear Weapons Tests has led to the development of procedures to verify that nuclear tests conducted in either country are below the 150-kt yield limit. In the adopted method, we use underground cables to monitor the spherically expanding shock front generated by the explosion. Measurements are made in the hydrodynamic zone, a close-in region where the high stress in the shock front completely dominates the shear strength of the rock, and the rock behaves like a fluid. Total released energy (i.e., yield) is determined by comparing the measured data with reference cases obtained from other tests or from detailed numerical modeling. For the United States, the Explosion Effects Physics and Monitoring Section of P-15 is responsible both for acquiring the on-site data (using techniques developed at Los Alamos) and for interpreting the results.

Recently, emphasis in arms control has shifted to the detection and identification of possible nuclear tests in countries for which on-site measurements are not possible. For underground tests, long-range seismic methods are required. Besides giving a yield estimate (for which a factor of 2 uncertainty is typical), these methods also need to discriminate between underground explosions and earthquakes and between chemical and nuclear explosions.

The two studies highlighted below were performed by Tom Dey (formerly with P-15, now with EES-5). They show how our extensive modeling capability, which was developed for treaty verification, is being used to examine issues related to the seismic detection of clandestine nuclear-weapons tests. The first deals with the issue of cavity decoupling as a means of concealing yield; the second, with the influence of overburden pressure on the seismic signature.

Determining yield by either the seismic or hydrodynamic methods depends significantly on conditions in the immediate vicinity of the explosive device. But one might intuitively expect that both methods would be influenced to a comparable degree by such local effects. We were therefore surprised when two independent computational studies of explosions in spherical underground cavities led to apparently contradictory conclusions. A study that examined coupling to seismic waves indicated an enhancement of signal (and hence of apparent yield) over a range of increasing cavity radii, whereas a hydrodynamic shock study gave inferred yields that monotonically decreased with cavity size. Which was correct? In a recent study, the computational tools used for the hydrodynamic zone were extended to include the more distant elastic zone, where the material response is linear and energy is in the form of seismic waves. Thus, a single model could treat the effects of cavity coupling on both of the yield measurement methods. The results of this work, as shown in Figs. 31 and 32, confirm the original, disparate studies—there is a difference. Enhanced coupling or decoupling in the seismic regime is essentially independent of the same effects in the hydrodynamic regime. The seismic enhancement depends on the rock type: the results shown here are for granite; the effect is lacking in tuff. It appears that the specific energy retained behind the shock front in the

Fig. 31. Coupling in the hydrodynamic regime, as gauged by the apparent to true yield ratio, as a function of initial cavity radius for a 1-kt reference explosion is shown.

cavity, in comparison with that retained in the rock, is the key to this behavior.

Only about 2% of the energy of an underground explosion is converted to seismic waves. Though most of the energy stays in the hydrodynamic zone, the above discussion shows that hydrodynamic models alone cannot predict seismic-zone behavior. Many key physical processes occur in the "inelastic zone," the transition region of lower shock pressures where the rock no longer behaves as a fluid and does not return to its initial state after passage of the wave (as elastic materials do). An important parameter in this respect is the rock's shear strength—that is, its ability to withstand the shear component of the applied stress during shock-induced deformation. Intuitively, the stronger the rock type, the more energy is dissipated in overcoming shear strength and the less energy is converted to seismic waves. However, no significant correlation between seismic coupling and rock strength has been observed in the field.

A series of computations was done in which shear strength had the dual role of both limiting initial cavity growth and also resisting subsequent cavity collapse under the ambient overburden pressure. Fig. 33 shows the seismic source waveform logarithmically as a function of relative time for a collection of strengths (relative to a reference case). The initial amplitude of the wave does indeed decrease monotonically with increasing strength. But in the three weakest cases, a subsequent collapse under the overburden pressure is apparent in the waveform. For these cases, there is no significant difference in the seismic spectrum at the low-frequency end—perhaps an explanation for the observed lack of correlation in the experimental data base. This work also provides a signature (the strong initial overshoot) of potential use in identifying cases in which overburden pressure, rather than rock strength, dominates the seismic coupling.

Fig. 32. Coupling in the seismic regime, as gauged by the steady-state reduced displacement potential (RDP), as a function of the initial cavity radius for the same cases as Fig. 31 is shown.

Fig. 33. Seismic-source amplitude (RDP) as a function of relative time for zero initial cavity radius and various shear-strength ratios is shown. From top to bottom at 0.2 s, the lines correspond to strength ratios of 1/16, 1/8, 1/4, 1/2, 1, 2, 4, and 8.

Trapping and Cooling Large Numbers of Antiprotons: A First Step Toward the Measurement of Gravity on Antimatter

M. H. Holzscheiter, R. J. Hughes, N. S. P. King, D. C. Lizon (P-15), R. E. Brown, T. W. Darling, P. Dyer (P-3), T. J. Goldman (T-5), M. M. Nieto (T-8), and Collaborators from Texas A&M University, NASA Ames Research Center, Pennsylvania State University, and the University of Colorado

We have been working toward the development of an experiment to measure the gravitational acceleration of antiprotons in the Earth's gravitational field, g . The experimental method consists of launching many ultracold antiprotons upwards against the gravitational force and measuring their TOF distribution. This distribution will exhibit a distinct cutoff, which is directly dependent on the value of g for the particle species under investigation.

An important ingredient for the successful execution of this experiment is the preparation of a large number of antiprotons at ultralow energies—the change in gravitational potential over the dimension of a (sensible) laboratory experiment is only a few tenths of a μeV , or a few mK on the temperature scale. Antiprotons are produced at large accelerator facilities in the GeV energy range. But only at a unique facility at CERN, the Low Energy Antiproton Ring (LEAR), can these high-energy antiprotons be accumulated and decelerated to energies as low as 5 MeV, which is still 10 orders of magnitude higher than what is needed for our experiment; we have developed a method to bridge this gap.

Several methods have been proposed and partially tested over the last five years by different groups. A radio-frequency-quadrupole (RFQ) accelerator could be used backwards to reduce the energy from 2 MeV to 20 keV, but it is extremely difficult for LEAR to reach the low input energy and the beam quality and time structure necessary for an efficient system. A test experiment to decelerate antiprotons from 2 MeV to 200 keV was therefore abandoned last year. An “anticyclotron,” an instrument used to decelerate antiprotons by collisions in a dilute gas while a strong magnetic field confines the decelerating antiprotons on a spiral trajectory, has successfully stopped antiprotons in a defined volume and has been used to study the annihilation of antiprotons with the gas. Any attempt to modify the performance of this system to extract the antiprotons before annihilation has so far failed, and a test experiment studying this method was also abandoned several years ago.

In the third method (incidentally, also the cheapest and simplest), antiprotons are passed through a thin foil of material (degrading foil). The antiprotons slow down by collisions with the nuclei in the material and are eventually captured and thus annihilate if the foil is thick enough. If one chooses the material thickness so that approximately one-half of the antiprotons emerge from the foil before annihilation, one finds a maximum number of low-energy antiprotons amongst the transmitted particles. Theoretical estimates, which are based upon empirical data for the ranges and the stopping powers of protons in different materials,

predict that the fraction of particles emerging from the foil with less than 30 keV will be approximately 1.2%, a respectable efficiency that is not much different from values expected for both the RFQ and the anticyclotron.

Charged particles at these energies can be captured and stored in electromagnetic field configurations called Penning Traps. Standard Penning Traps consist of a set of electrodes that generate an electrostatic quadrupole potential, which is superimposed onto a strong, axial magnetic field. Charged particles stored within such a configuration undergo a combination of a harmonic axial oscillation, a radial cyclotron motion (modified by the presence of the electric field), and a slow radial $E \times B$ drift motion. Generating a pure quadrupole potential is not mandatory for storage, and the axial trap dimension can be extended to match the trap phase space to the phase space of the accelerator output, which provides the antiprotons. At LEAR, for example, particles are typically delivered in a 200-ns bunch, which means that for 200 ns low-energy antiprotons emerge from the downstream side of the foil. Those with energies below 30 keV are turned around by the upstream electrode of the modified Penning Trap, and they return to the entrance electrode. The particle will be captured if the potential of the electrode is raised to 30 keV before the particle can reach it. However, one cannot afford to raise the potential before the last particles have entered the trap; thus, the minimum round-trip time for 30 keV is set at 200 ns (plus some allowance for rise time and jitter). The minimum axial dimension for our trap is thereby 50 cm. Such a system (the PS200 Catching Trap) has been constructed and has undergone preliminary tests at the Ion Beam Facility (IBF) at Los Alamos. The system was then shipped to CERN in early 1992 (Fig. 34).

The antiproton bunches in our setup exit from the LEAR vacuum through a thin titanium window. After passing through a set of parallel-plate avalanche counters (PPACs) used to monitor the position of the beam and through a gas cell used to fine tune the beam energy, the bunches reenter our vacuum system through another titanium window. Additionally, an NE110 scintillator, which is instrumented with a special high-current base, monitors antiprotons that annihilate in the grids that support the Mylar windows of the PPACs; this scintillator also supplies a picture of the temporal structure of the beam pulse. At this point, the particles have been slowed down from the initial 5.9 MeV when they left LEAR to approximately 4.0 MeV. The particles also acquired significant radial momentum through multiple scattering in the many layers of material that they passed through. But the strong magnetic field of our 6-T superconducting magnet serves as a strong focusing device, and by properly choosing the exact distance between the entrance window and the final foil and by fine tuning the magnetic field strength, one can focus the beam onto the entrance electrode of the trap.

A trigger pulse from the scintillator is delayed to allow for the TOF and for the 200-ns bunch length. This delayed pulse initiates the closing of the trap right after the last particle has entered the trap, thus capturing

Fig. 34. A schematic of the PS200 Catching Trap shows the system that was tested at the IBF at Los Alamos and shipped to CERN in early 1992 for test experiments with the LEAR.

the antiprotons with energies below 30 keV. After a chosen storage time (typically varying between 0.5 s and several minutes), we lower the potential of the upstream electrode over a 0.5-s time period to slowly release the antiprotons remaining in the trap toward a microchannel-plate detector (MCP). The MCP generates a time-of-arrival spectrum (i.e., the TOF between the trap and the MCP is negligible on this time scale), which directly reflects the energy distribution of the particles in the trap just before the release. We identify the particles by observing the counts of antiprotons, as well as high-energy pions produced by antiproton annihilation on the surface of the MCP with scintillators placed around the outside of the magnet dewar. Setting a proper coincidence requirement virtually eliminates all background, and the number of antiprotons leaving the trap can be detected with a fixed, calculable efficiency (approximately 7% for most of our runs).

Antiproton beam time at LEAR is a very rare commodity, and only a few shifts were made available for our test experiments. During the summer of 1992, one shift was used to tune up the transfer beam line from LEAR to our experiment to establish the proper energy degradation caused by our set of windows, foils, radiation baffles, and gas volumes. Once the proper operation of the experimental equipment was

established, we were able to attempt an actual capture. But because of beam-tuning problems in LEAR, the beam spot was much larger than our experiment could tolerate. Nevertheless, the very first shot from LEAR resulted in a successful capture of about 50,000 antiprotons. We conducted a number of systematic studies to investigate the focusing effect of the magnetic-fringe field, the maximum electrical potential that could be applied, the storage time (which depended on the residual gas pressure in the system), and the efficiency of our detection system. During the shutdown period at LEAR, we upgraded the beam-line monitoring by improving the PPAC detector, which was calibrated with the tandem accelerator at the IBF in Los Alamos. We also improved the mechanical structure of the PS200 Catching Trap for better thermal properties.

In the summer of 1993, we again joined the LEAR team during their machine-development time to test our system. Based on the signals from our NE110 scintillator and the new PPAC system, the LEAR team improved beam focusing in a relatively short time and delivered a beam spot of less than 3 mm in diameter to our entrance window. We were thus able to capture as many as one million antiprotons from a single shot from LEAR. Figure 35a shows a typical spectrum of particles released from the trap a few seconds after capture. By then, the particles have thermalized amongst themselves by Coulomb interaction, and the energy has been redistributed in all degrees of freedom. The spectrum shown represents a Maxwell Boltzman distribution with a mean energy of approximately one-third of the well depth, fully supporting this statement. Our

Fig. 35. Typical spectra show the release of particles from the trap a few seconds after capture (a) and 38 s after capture (b).

continued studies established an overall antiproton capture efficiency, which includes beam loss in transport between LEAR and the experiment, at around 0.25%. This capture efficiency is only a factor of 5 below the idealistic theoretical prediction (Fig. 36).

When we extended our storage time to longer periods, we were surprised by a sudden shift in the energy spectrum to much lower values. The explanation was more than exciting to us: the antiprotons entering the trap, as well as those captured in the trap, generated electrons by ionizing residual gas molecules. These electrons become trapped as well and lose energy (through synchrotron radiation) with a 300-ms time constant. In turn, the antiprotons interact with these electrons via Coulomb interaction and transfer energy to them, being cooled to an equilibrium temperature determined by the effective noise temperature in the trap electrodes. Figure 35b shows a spectrum of particles released 38 s after capture. The total number in the spectrum has not changed, but all particles have collected in the low-energy portion of the distribution. The observed mean energy in this distribution is below 100 eV (the actual energy is probably even lower).

From the cooling times observed, we conclude that approximately one billion electrons were present in the central region of the trap. This large number of electrons represents a reasonable high-density electron plasma in which the antiprotons are imbedded. This plasma not only causes the cooling as observed but most likely also affects the motion of the antiprotons in the trap and is responsible for the distinct and regular structure superimposed upon the Maxwell-Boltzmann distribution at higher energy. These effects present a number of interesting physics challenges using antiprotons as a unique probe for diagnostics.

These test runs established our capability of capturing significant numbers of antiprotons, cooling them through a high-density electron plasma, and containing them for time periods long enough to allow us to consider further experiments. One of the most important practical results established during these experiments is the capability of the LEAR team to tune up the transfer beam line for our experiment in a very short time after serving another experiment. This capability will allow true parasitic operation during which LEAR serves a "main user," but occasionally a new fill of antiprotons can be directed to the "parasitic user." Parasitic operation will thus allow us to continue our development of the PS200 Catching Trap without significantly affecting the LEAR operation, and it will open interesting opportunities for new experiments that require very low-energy antiprotons without putting high demands on the precious antiproton beam time. Discussions with several groups interested in such experiments have been initiated, and a formal proposal has recently been submitted to CERN.

Fig. 36. The overall capture efficiency of antiprotons, which includes beam loss in transport between LEAR and the experiment, is around 0.25%. This capture efficiency is only a factor of 5 below the idealistic theoretical prediction.

Nuclear-Energy Production Without a Long-Term High-Level Waste Stream

C. D. Bowman, F. Venneri, and L. S. Waters (P-17)

Accelerator-driven systems for the resolution of several major problems in the nuclear energy field have been under study for several years. Perhaps the concept of greatest interest involves a system that derives energy from thorium and concurrently destroys its long-term, high-level waste stream by transmutation. The three main objectives of such a system are similar to those of fusion—that is, to provide energy for an unlimited period of time (the energy content of thorium could supply the world's needs for many thousands of years); to operate in a subcritical mode so that nuclear runaway would be absolutely impossible; and to destroy the accompanying long-term, high-level waste stream. The difference, however, is that these objectives can be realized within the next decade through fission using the technology described in this research highlight. This technology might also be applied to the transmutation of waste from commercial nuclear-power production and to the destruction of excess weapons plutonium.

The system (Fig. 38) operates by providing an intense, thermal neutron flux to burn fissile material and to transmute both fission products and any higher actinide materials. When a medium-energy intense beam (average of 50 to 100 mA at 500 to 1,000 MeV) of protons or deuterons that enter from the top interacts with a spallation target, about 15 to 30 fast neutrons are produced for each proton. A surrounding graphite blanket slows the neutrons down to thermal energies, and they induce fission in the "fuel," which is circulated through the blanket. The system must be designed so that there is no possibility of a self-sustained chain reaction. Fluxes as high as 5×10^{15} n/cm²-s can be achieved in the blanket volume with a neutron multiplication of 20 or equivalently with an effective multiplication factor of $k_{\text{eff}} = 0.95$. Heat from fission in the blanket is converted to electrical power with more than 40% efficiency. About 10% of this power is drawn off and used to drive the accelerator to produce the neutrons. Because of the power used to keep the accelerator running, the power-conversion efficiencies must be made as large as possible. Molten-salt fuel systems with structural materials that have very low corrosion rates and very low vapor pressure (a valuable safety and engineering feature) can operate at high temperatures without degrading the flowing material. Molten salt also has a high thermal-to-electrical conversion efficiency of up to 44%; this valuable feature allows for a much larger electrical power output than that of conventional, lower-efficiency light-water reactors (LWRs). (LWRs operate at the same fission power in spite of the power drain that occurs when the accelerator is operated.) The molten fluoride salt LiF-BeF₂, which was used in the Oak Ridge Molten Salt Reactor Experiment (MSRE) for 5 years in the late 1960s, appears to be the best candidate carrier salt for the actinide and fission-product fluoride salts.

The most promising design concept uses a molten LiF-BeF₂ salt target, which is surrounded by a uranium layer for converting neutron kinetic energy into additional neutrons. This neutron-generation part of the assembly is surrounded by a graphite-moderated multiplying blanket. The salt-uranium neutron production system in the target

allows efficient neutron production and low-parasitic neutron absorption because of its small size and the presence of the surrounding fission-product transmutation region. Because the proton or deuteron beam interacts mainly with the LiF-BeF_2 salt, the target produces few waste products.

The most promising design concept of this accelerator-driven system is a neutron-production assembly that consists of a molten LiF-BeF_2 salt target surrounded by a layer of uranium. Neutron kinetic energy in the layer of uranium is converted into additional neutrons. This neutron-production portion of the assembly, which is surrounded by a graphite-moderated multiplying blanket, efficiently produces neutrons and allows for low parasitic neutron absorption because of the small size of the target and the presence of the surrounding fission-product transmutation region. This region keeps the thermal neutrons, which are generated in the blanket, from being parasitically absorbed in the target. Because the proton or deuteron beam interacts mainly with the LiF-BeF_2 salt, the target produces few waste products.

The same LiF-BeF_2 mixture that constitutes the target salt also carries the plutonium and the thorium fuels as fluorides. The molten salt circulates through a bed of graphite spheres, which constitute the neutron moderator, and into intermediate (salt-to-salt) heat exchangers that are submerged in the tank containing the salt. The breeding of ^{233}U from thorium and the bulk of the power generation occur within this salt, which is at the same time the target, fuel, and heat-exchanging fluid. The fission products, isolated for transmutation through the processing of a small slip stream, are placed in special high-flux regions just outside the uranium portion of the target.

Once the fuel is in the blanket, the only process that has to be performed more or less continuously during power production is the separation of fission products from the fuel. At high-thermal neutron flux (which is associated with low inventory), fission products must be separated rapidly to avoid deterioration of the fuel's reactivity. Continuous on-line processing of the liquid fuel makes this possible. Moreover, separation processes are needed to avoid the introduction of additional external materials (i.e., solvents, catalysts, and reagents), which could become part of the radioactive waste stream. Physical chemistry processes are favored; they perform these separations by fractional evaporation, precipitation, electrolysis, solubility, and centrifugation. Volatile fission-product fluorides would be separated from the fuel using helium sparging—that is, helium gas is sprayed as bubbles into the fuel to separate the volatile fluorides from the fuel.

Fig. 38. The most promising design concept uses a molten $^7\text{LiF-BeF}_2$ salt target surrounded by a uranium layer and a graphite-moderated multiplying blanket. Molten $^7\text{LiF-BeF}_2$ salt carries the thorium, the bred ^{233}U , and all minor actinides generated during the current-energy production or previously in LWRs. The molten salt in this loop circulates through a neutron moderator, which consists of a bed of graphite balls, and then into intermediate (salt-to-salt) heat exchangers where all the heat generated in the blanket is eventually removed. Thorium breeding and the bulk of the power generation occur within the main loop, which is at the same time the target, fuel, and heat-exchanging fluid; a simple assembly design is thus provided. The fission products, isolated for transmutation, are placed in special high-flux regions near the center of the blanket.

A design of this system with realistic dimensions, power densities, and liquid-flow and heat-transfer rates has been completed using materials that are compatible with the molten salt, as established by the MSRE at Oak Ridge. The performance of this system has been calculated with a Monte Carlo statistical method that allows us to calculate arbitrary geometry and energy-differential cross sections and neutron flux; this method provides us with a detailed account of resonance structure. The code, Los Alamos High Energy Transport (LAHET), has been used to predict the transport of protons and to calculate neutron conversion. This code is coupled to the Monte Carlo Neutron and Photon Transport Code (MCNP), which also allows us to calculate in detail the neutronic performance of the system. An initial loading of material is followed by successive Monte Carlo calculations through changes in composition (as the higher actinides build up) and through the accompanying changes in the neutron spectral shape until equilibrium is reached. The calculations take into account the flow (by neutron capture and decay) through 40 nuclides between ^{232}Th and ^{252}Cf . Because the flowing liquid allows for the constant removal and replenishment of the salt constituents, a true equilibrium, which is in contrast to the situation with solid-fuel systems, may be established. The usual properties of the system, including k_{eff} , temperature coefficients, etc., are calculated.

The next step in the development of this concept is an experiment at the Los Alamos Meson Physics Facility (LAMPF) using the full 1-mA beam to drive a subcritical system with $k_{\text{eff}} = 0.95$. The system will operate at a thermal fission power up to 20 MW and will demonstrate materials compatibility, accuracy of the calculated operation dynamics, performance of heat exchangers, and many other important features of the design. The final program will demonstrate the substantial power production from thorium using an accelerator-driven system. Supporting experiments in nuclear physics have already begun at the Weapons Neutron Research (WNR) Facility and the Manuel Lujan, Jr., Neutron Scattering Center (LANSCE).

The predicted performance of the target will be verified at the WNR Facility by experiments that include a full-scale target surrounded by a manganese-bath absolute neutron detector with a 2.5-m-diam by 3-m-long outer dimension. The purpose of this experiment is to examine the proton-to-neutron conversion efficiency for several different target compositions. A second set of experiments is under way at LANSCE to measure the fission cross sections for several key actinide nuclei (e.g., ^{238}Np and ^{242}Am) with half-lives of the order of a few tens of hours. The combined use of the Omega West Reactor, the IBF, and LANSCE is necessary to complete these fission cross-section measurements. No other set of facilities in the world can match those at Los Alamos for these fission studies.

The planned experiment at LAMPF would operate for about 7 years and will require nearly all of the LAMPF beam; this experiment could become the primary driver behind the continued operation of LAMPF. Fortunately, the experiment can operate synergistically and concurrently with the other main LAMPF programs so that the pion and neutrino experiments could continue to be conducted and the LANSCE and WNR facilities could continue to be operated on an enhanced schedule.

P-1: High Energy-Density Physics

Collaborations on Deuterium-Tritium Physics at the Tokamak Fusion Test Reactor

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During 1993, the Tokamak Fusion Test Reactor (TFTR) began experiments using tritium fuel. Personnel from P-1 were involved with the diagnostics and physics of these extremely exciting and important experiments. The absolute calibrations of alpha-particle diagnostics were performed with the help of Los Alamos personnel. The scintillators used in lost-charged-fusion-product detectors were characterized with the ion beams from the Ion Beam Facility, and the scintillator material that was used in the high-flux deuterium-tritium (D-T) experiments was chosen. The neutron-activation diagnostic was upgraded and used as the standard for the 14-MeV neutron emission from TFTR. Neutron-activation measurements coupled with the Monte Carlo Neutron and Photon (MCNP) transport code provided the most accurate determination of the fusion power and alpha-production rate in TFTR D-T experiments. Fast-optical diagnostics of the light emitted from solid pellets (both lithium and deuterium) with spatial and spectral resolution helped optimize the use of the pellets for enhancing TFTR performance. We also used these optical measurements to understand the alpha charge-exchange process in the pellet cloud in support of the fast-optical diagnostics. Physics experiments included measurements of the rotational transformation of the magnetic field (i.e., variations in the ablated pellet light with radius were used to make these particular measurements); fast-ion transport from triton burnup and short tritium beam pulses; and the isotopic scaling of energy transport.

Intense Diagnostic Neutral Beam

R. R. Bartsch [(505) 667-9977], W. B. Hinckley, R. J. Kasik, D. J. Rej (P-1)

The intense diagnostic neutral beam (IDNB) project is developing a neutral probe beam for diagnostic use on hot, dense, burning fusion plasmas, such as in the International Thermonuclear Experimental Reactor (ITER). Charge-exchange-recombination spectroscopy with an atomic hydrogen beam can be used to determine thermal-ion temperatures and velocities, as well as fusion-alpha-particle density and energy distributions along the beam path. The diagnostic beam under development is designed to have sufficient intensity so that the beam-spectroscopy signal will be greater than the bremsstrahlung background signal to permit measurements with a single pulse. We have achieved ion-beam pulses of 10 to 20 kA at drive voltages up to 96 kV using a flashover-anode, magnetized ion diode similar to diodes used at Sandia National Laboratories on ion-beam fusion experiments. This ion beam is presently being used to evaluate the physics of a hydrogen-puff-valve neutralization section. A more complex, plasma-anode, magnetized-ion-diode design, currently under development, will be used in the final beam source because of its improved ion purity, beam control, and reproducibility.

Electrical Resistivity and the Equation of State of Strongly Coupled Plasmas

J. F. Benage, Jr. [(505) 667-8900] (P-1)

A plasma is strongly coupled when the electrical energy between ions in the plasma has become equal to or greater than the thermal energy. Under these conditions, the equations generally used to describe the properties of plasmas are no longer valid. Many theories have been developed to describe the properties of a strongly coupled plasma, but little experimental data exist to check these theories. For this reason, we are conducting experiments to measure the electrical resistivity of a dense, strongly coupled aluminum plasma. The aluminum plasma is produced by passing an electrical current through a 0.004-in. pure aluminum wire. The current heats the wire to temperatures up to 20 eV while the density is kept near solid by encapsulating it in high-density lead glass. Then by measuring the current through the plasma, the voltage across it, and the cross-sectional area of the plasma, we can determine the resistivity. We have completed our first set of measurements on these plasmas this year and have compared our results with simulations performed by X-5 using the Sesame tables. These results indicate that the tables do not contain the correct resistivity of aluminum under these conditions. Comparison with other theories will require a more accurate temperature measurement than what we have obtained thus far. When we have obtained more accurate temperature measurements, we will also test the equation-of-state (EOS) models in the Sesame tables. We do this by comparing the simulations done by X-5 with the temperature and dynamics of the plasma. These quantities, which are sensitive to the EOS model used in the simulation, provide an unambiguous test over the range of conditions produced in the experiment.

Pegasus II Operations

J. C. Cochran [(505) 667-1227] (P-1)

On September 15, 1992, Pegasus II fired its first experimental facility shot, thus launching the Laboratory's largest operational pulsed-power capacitor bank. At a maximum stored energy of 4.3 MJ and a peak current in excess of 12 MA, Pegasus II gives the Laboratory a world-class, pulsed-power facility for experimental use. Such a facility is especially critical at a time when the Laboratory must assess its future direction because of the decrease in underground testing, which rapidly occurred following the end of the cold war. Pegasus II, which is part of the Laboratory's AGEX (AboveGround EXperiments) program, will play an important role in examining weapons-physics issues as the emphasis in testing and design switches from underground testing to aboveground experiments. During FY93, Pegasus II fired its first shot series dedicated to a weapons-physics issue previously addressed primarily in underground testing. In this initial series of experiments, participants from X-5, J-7 (now DX-17), J-8 (now DX-12), P-1, P-3, P-14, P-15, and EG&G Energy Measurements, Inc., collaborated to produce important data. These data will be used in other experiments scheduled for FY94 to provide a better understanding of the behavior of matter under conditions encountered in nuclear-weapons testing.

Fundamental Electrothermal Gun Behavior

H. A. Davis [(505) 667-8373] (P-1), B. A. Kashiwa (T-3)

The military is interested in electrothermal guns for increased tank-armor penetration, extended-range artillery, and the soft launch of guided munitions. These guns are expected to perform better than conventional guns because significant electrical energy is used to control the combustion of chemical propellants. The objective of this work is to understand fundamental gun behavior by direct observation and computer modeling of the interaction of a dense, electrically driven plasma with a liquid. In our experiment, the plasma was produced by electrically exploding a thin wire surrounded by water in a high-strength polycarbonate tube contained inside stainless-steel housing. Measurements included load current, voltage, chamber and barrel pressure, in-bore time-resolved projectile position and velocity, multiframe x-radiography, and time-resolved visible-light photography. While the plasma was forming, the current path became highly irregular and was punctuated by hot spots. Both x-ray and visible-light images later in time showed an expanding cloud with a rough surface that separated the gas from the liquid. Initially, the scale size was similar to the scale of the hot spots observed during the wire explosion. As the gas cavity expanded, the small-scale structure gave way to larger structures. Results of computer simulations suggest that growth of the largest structures (bubbles and spikes), which are visible in the flow, is determined by a sequence of well-known hydrodynamic processes. A classical Rayleigh-Taylor process appears to be responsible for the growth of structures at the earliest times. This process is followed by a Richtmyer-Meshov coasting process whereby the growth of structures occurs through inertial effects. Finally, the strong relative flow (at the boundary) between the more slowly moving liquid and the gas that rapidly escapes from the chamber leads to a Kelvin-Helmholtz flow, which further accelerates the growth and distortion of the large structures.

Gigabar Shock Propagation

R. D. Fulton [(505) 667-2652], G. A. Kyrala, J. K. Studebaker, R. E. Eitland (P-1), J. A. Cobble (P-4), G. T. Schappert (P-DO)

The Los Alamos Bright Source (LABS II) is a state-of-the-art laser facility where experiments relevant to the AGEX II program are conducted. One such series of experiments involves focusing LABS II (i.e., a high-brightness eximer laser that produces 0.2 J of energy with a 300-fs pulselength and has a peak-irradiance capability of 5×10^{18} W/cm²) onto thin foil targets. If we consider the momentum transfer that is simply due to the reflection of light at these irradiances, pressures in excess of a gigabar are generated in the laser-plasma interaction. Past experiments on thick targets have demonstrated temperatures of over a keV in the emitting region. These temperatures combined with measured electron densities imply that particle pressures are also in excess of a gigabar. At these pressures, a new instability is postulated whereby small variations in the initial shock strength leads to differential ionization as the shock propagates. The differential ionization creates an uneven electron-density profile, which in turn alters the shock-propagation characteristics. This would constitute a new instability, which can occur in the absence of interfaces. The planned experiment will involve shooting a thin foil with the laser and studying the stability of the propagation of the shock wave set up by the extreme impulsive pressures created in the interaction region. A small fraction of the incident laser will

be split off and directed onto the backside of the foil through a variable delay line. An imaging system with micron resolution will then record images of the shock breakout on a shot-to-shot basis. These images will allow us to construct a time sequence of shock-breakout images and then determine which target conditions lead to or suppress the instability.

X-rays from High-Z Materials

R. D. Fulton [(505) 667-2652], G. A. Kyrala, J. K. Studebaker (P-1), J. A. Cobble (P-4), G. T. Schappert (P-DO)

LABS II is a state-of-the-art laser facility where experiments relevant to the AGEX II program are conducted. One such series of experiments involves focusing LABS II (i.e., a high-brightness eximer laser that produces 0.2 J of energy with a 300-fs pulselength and has a peak-irradiance capability of $5 \times 10^{18} \text{ W/cm}^2$) onto solid targets. For aluminum, we have observed a conversion efficiency of a few percent into the hydrogen- and helium-like aluminum resonance lines around 2 keV. The lines are emitted in 30 ps, which produces a soft x-ray source of 10^{14} W/cm^2 . These soft x-ray intensities can be very useful for a number of AGEX experiments, albeit on very small spatial scales and short time scales. This emission time is consistent with recombination time scales and can be made shorter by going to an excitation-dominated system as opposed to recombination. We will explore this possibility by going to higher-Z targets. A titanium target with resonance line energies near 4.5 keV will be next. Because titanium has a shorter radiative lifetime, its emission time should relate more closely to excitation-deexcitation rates of a few picoseconds. If the conversion efficiency remains constant, the titanium target will be a unique x-ray source. Following these experiments, we intend to continue to explore higher-Z targets until we can no longer excite hydrogen- and helium-like states because of our limited laser energy.

Nonlinear X-ray Processes

G. A. Kyrala [(505) 667-7649], R. D. Fulton, D. Oro (P-1), G. T. Schappert (P-DO)

We are investigating whether we can observe the nonlinear interactions of x-rays with matter. Because these interactions require that two or more simultaneous photons be present for observation, they depend on a higher power of the irradiance. That power is usually equal to the number of photons involved in one interaction. Because the coupling is weak, high irradiances are needed to observe the nonlinear interactions. Larger irradiances are required to observe higher-order processes. As a first demonstration, we are investigating whether the highest brightness laboratory x-ray source (i.e., x-rays from a LABS II irradiated aluminum target) can be used to observe two-photon absorption in a chlorinated target. Early calculations of the relevant cross sections indicated that the x-ray flux is sufficient to generate a few thousand two-photon events per laser shot. Thus, we should be able to observe the effect if competing single-photon backgrounds do not mask it. We are currently evaluating these competing single-photon backgrounds, and we are designing the target and the experiment to maximize the ratio of the two-photon-to-one-photon signals.

Vacuum Ultraviolet Light Source

G. A. Kyrala [(505) 667-7649], R. D. Fulton, J. K. Studebaker, W. M. Wood (P-1), G. T. Schappert (P-DO)

LABS II is a state-of-the-art laser facility where experiments relevant to the AGEX II program are conducted. One such series of experiments involves focusing LABS II (i.e., a high-brightness eximer laser that produces 0.2 J of energy with a 300-fs pulselength and has a peak-irradiance capability of 5×10^{18} W/cm²) onto thin foil targets. The low-intensity pre-pulse emitted by the eximer amplifier explodes the foil into a dense, cool plasma. When the timing is varied, the main pulse can be made to interact with a long scale-length plasma, the exact parameters of which can be tailored. Similar experiments conducted in gas jets at much lower densities have produced harmonics of the incident laser past the 50th harmonic. For the 308-nm light of the LABS II, the 50th harmonic would correspond to energies in excess of 200 eV. The efficient production of semitunable radiation near 200 eV from a table-top laser system would be an extremely important development capable of supplanting synchrotrons. The harmonics we will investigate will be plasma-produced harmonics as opposed to the atomic harmonics produced in gas jets. Because these harmonics will be produced at a much higher density, the potential for a much greater conversion efficiency exists. The specific issues that we will address are the conversion efficiency as a function of energy, the emitted angular distribution of the harmonics, and the coherence of the harmonics.

Implosion Physics on Pegasus II

J. S. Ladish [(505) 665-6446] (P-1)

The Pegasus II high-voltage, pulsed-power facility is an ideal facility for performing a variety of experiments relevant to the weapons-physics needs of the Laboratory. With an electrical stored energy in excess of 4 MJ and peak currents of up to 10 MA, the system is capable of imploding cylindrical metal foils to produce an axial plasma source with temperatures of the order of 50 eV at present. This plasma source is a source of soft x-rays with an energy-conversion efficiency (electrical to radiation output) of a few percent. The time compression is a factor of approximately 10 between the time scale of the implosion event and the width of the burst of x-rays at the time when the foil collapses on axis. With heavy loads (on the order of grams), higher efficiencies are possible, and we can achieve solid-liner velocities that can address important weapons-physics issues. These experiments involve sophisticated diagnostics, many of which are similar to, or identical with, those fielded in underground experiments at the Nevada Test Site (NTS). These experiments also provide a means of maintaining the critical skills of personnel as the underground-testing program is reduced in intensity. This activity involves several P-Division groups, as well as personnel from other divisions.

Plasma Decontamination

D. J. Rej [(505) 665-1883], B. P. Wood (P-1), J. C. Martz (NMT-5), D. P. Taggart (CST-7)

The use of a CF₄/O₂ radio-frequency plasma to etch materials is a well-established technology in microelectronics manufacturing. Plasma etching has also been demonstrated with plutonium and uranium, both of which form volatile hexafluorides. Work is under way in NMT-5 to

demonstrate that this process can be used to remove plutonium contamination from small objects. Concurrently, there is an effort in P-1 to show that a variety of plasma-processing techniques can be scaled up to industrially useful sizes in an 8,000-l vacuum chamber. We are developing a collaboration between these individual efforts to determine whether large objects, such as whole glove boxes, can be decontaminated by the plasma-etching process. Using current methods, the estimated cost of decommissioning a glove box is comparable with that of acquiring a new one, and the decontamination process produces additional hazardous, actinide-contaminated chemical and solid waste. In contrast, plasma etching produces little collateral waste during processing. The by-products are gaseous and generally nonhazardous except for PuF_6 , which would be captured and recycled. In addition, worker exposure to radiation and hazardous chemicals would be minimized.

Thin-Film Deposition with Intense, Pulsed Ion Beams

D. J. Rej [(505) 665-1883], H. A. Davis, W. J. Waganaar (P-1), R. J. Faehl (X-5), R. E. Muenchausen (MST-7), G. Johnston (University of New Mexico), M. O. Thompson (Cornell University), K. Grabowski (Naval Research Laboratory)

Over the last two decades, remarkable progress has been made in the understanding and development of intense, light ion beams. Although the primary application driving the development of this technology is inertial-confinement-fusion (ICF) energy research, several intriguing materials-processing applications have recently emerged. Because only a short range of ions are in matter, applications usually involve the surface modification of materials, e.g., implantation, alloying, etching, and glazing. Thin-film deposition appears especially well suited for intense ion beams. When a beam is propagated into a target, substantial amounts of target material may be evaporated and ionized. The ablated plasma may then be deposited at record rates onto an adjacent substrate. Pulsed-ion-beam deposition is being studied in P-1 with the Anaconda intense light-ion-beam accelerator equipped with an applied radial-magnetic-field-insulated ion diode. Typical beam parameters for our recent experiments include 0.4 MV of energy, a 30-kA peak electrical current, and a 400-ns pulse width comprising hydrogen, carbon, and oxygen ions. $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ polycrystalline ceramic films, which are of interest for high- T_c superconductor applications, have been deposited onto a variety of substrates. Congruent evaporation is observed with the 1:2:3 target stoichiometry preserved in the thin film to within 10%. Recently, diamond-like carbon films have also been prepared by ablating graphite targets with a focused ion beam.

Development of Intense-Ion-Beam and Accelerated-Plasma Technology for Advanced Manufacturing

J. T. Scheuer [(505) 665-6525], D. J. Rej, K. F. Schoenberg (P-1)

In collaboration with the 3M Corporation, members of P-1 are developing intense-ion-beam and accelerated-plasma technologies for advanced and environmentally conscious manufacturing. The principal objective is to use Los Alamos facilities and expertise in these directed-energy technologies to develop new, cost-effective, and environmentally conscious manufacturing techniques. Both coaxial plasma accelerators and intense ion beams have already demonstrated laboratory proof-of-principle manufacturing capabilities. This project, which will help develop these technologies using recent Los Alamos advances in

magnetic nozzles and long-pulse, magnetically insulated ion diodes, will ultimately provide 3M Corporation with a prototype, directed-energy manufacturing system. This research will optimize coaxial-gun-generated plasmas for specific industrial applications. Coaxial-gun-generated plasmas will be used to process a variety of target materials. Etch rate and target quality will be assessed as functions of parameters that control the gun operation. Tests of optimized coaxial-gun-generated plasma processing will be conducted by 3M Corporation and Los Alamos personnel using 3M's processing facilities. Intense ion beams from the Anaconda accelerator will first be used to study beam interactions with a variety of targets for materials-processing applications. Beam quality and target-process quality will be assessed with a view to commercial manufacturing requirements.

Penning-Trap Fusion Experiment

D. W. Scudder [(505) 665-1892], D. C. Barnes (T-15), M. H. Holzscheiter (P-15), L. Turner (T-15)

We are beginning a series of experiments to determine if the excellent confinement of Penning traps can be used to confine fusion plasmas. Penning traps, unlike other confinement schemes used for magnetic confinement fusion, confine nonneutral plasmas; their confinement can be absolute. They have not been used for fusion before because the average density that can be confined in a Penning trap is too low for fusion experiments. We are attempting to overcome this limitation by confining a plasma with a high-density focus at the center where the local density will be orders of magnitude higher than the average density. A Penning trap confines a one-species plasma in the radial direction with a straight solenoidal magnetic field. Axial confinement is provided by a quadrupole electric field. In this experiment, the magnetic and axial fields are balanced to provide spherical equilibrium. Spatial nonuniformity is achieved by injecting particles (electrons in initial experiments) with nearly zero-canonical angular momentum. As long as this velocity distribution is preserved, each particle will return on each orbit to a focal spot in the center of the machine. We are conducting initial experiments with a trap of about 1 cm in diameter with an 8-kG magnetic field and a 100-keV electric field.

Radiation Collapse in a z-Pinch Plasma

J. S. Shlachter [(505) 665-1888], F. J. Wysocki (P-1)

Plasmas in a z-pinch configuration (i.e., an axial current that produces an azimuthal magnetic field) are in a static equilibrium where inward and outward radial forces are balanced at a unique value of current called the Pease-Braginskii current. For a pure hydrogen plasma, the Pease-Braginskii current is approximately 1.4 MA; this value is substantially reduced for higher-atomic-number plasmas. When the plasma current exceeds the Pease-Braginskii current, bremsstrahlung-radiation losses will predictably be greater than the ohmic power input, and the magnetic-field pressure will cause the plasma column to collapse radially inward, thus producing extremely high densities. Our primary goal is to test this prediction experimentally by diagnosing the behavior of a plasma operating in the regime where the Pease-Braginskii current is exceeded. In addition to producing unique physical conditions in a controllable experimental environment, we hope to successfully achieve a radiation collapse that will perhaps provide an attractive approach to the production of intense x-rays. A Mather-type dense-plasma focus, a

device that collapses or focuses plasma at the end of a coaxial discharge, has been designed to achieve our research objectives. Hardware for this 250-kJ facility has been fabricated; assembly of the machine is now under way. The experimental apparatus will be used with a uniform gas load and will allow us to achieve high repetition rates of tens of discharges per day. In addition, diagnostic access in the focus region will allow us to simultaneously measure plasma temperature, density, x-ray emission, and stability.

Plasma-Immersion Ion Implantation for Semiconductor Film Growth

M. G. Tuszewski [(505) 667-3566], J. T. Scheuer (P-1)

An interdisciplinary team of plasma and semiconductor physicists is developing a novel plasma implanter for thin-film growth on semiconductors with unprecedented control. The scientific objectives of this project are (1) to construct a compact, inexpensive, and high-throughput implanter based on an inductive plasma source and on the plasma-immersion ion implantation (PIII) technique; (2) to extend the PIII technique to higher frequencies, lower voltages, and higher dose rates; (3) to characterize, optimize, and control the plasma-species concentrations and impurities; and (4) to generate semiconductor dielectrics and alloys for new electronics-device technologies. We have constructed most of the PIII implanter, including a 0.5-MHz radio-frequency inductive source. Characterizing the plasma will involve comparing the plasma density and uniformity of several radio-frequency sources and controlling species content, contaminants, and particulates. Semiconductor applications will include silicon and III-V oxide and nitride thin films. These will be analyzed by co-investigators from MEE-11 (now MST-11).

Tokamak-Physics-Experiment Collaboration

M. G. Tuszewski [(505) 667-3566], G. A. Wurden, K. F. Schoenberg, C. W. Barnes (P-1)

The tokamak physics experiment (TPX) involves a multi-institutional device that will be built at Princeton University once the TFTR is shut down. The mission of TPX is to develop the scientific basis for a compact and continuously operating tokamak fusion reactor within a budget of about five hundred million dollars. As part of the TPX physics design team, P-1 physicists contribute to the project in four different areas. First, Fokker-Planck calculations of neutral-beam, fast-ion ripple losses were made. Typical ripple-loss power fractions were found to be about 5%. The lost power was very localized on the outboard midplane of the plasma torus and caused peak heat loads of 2 to 3 MW/m² on the passive stabilizer plate. This information was essential for the design of the stabilizing shell. Second, disruption avoidance and control was considered for TPX. Current-profile control from lower-hybrid and electron-cyclotron current drives can avoid disruption-probable regions in the operating parameter space. Countermeasures, such as the use of an active-feedback control device or an ergodic divertor, were planned to prevent or to mitigate plasma disruptions. In addition, TPX was designed to withstand the most serious anticipated disruptions. Third, a complete set of TPX day-one diagnostics was identified and cost estimated. Finally, the above studies were summarized in the TPX physics design document, which was carefully edited.

Plasma-Source Ion Implantation

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Implantation of gaseous ions into metals is an environmentally conscious process, which can produce hard, corrosion-resistant, low-friction surfaces. Widespread industrial use of ion implantation has been limited because conventional ion-beam implanters are too expensive, complicated, and slow. An alternative is plasma-source ion implantation (PSII). In this process, an object is immersed in a weakly ionized plasma and then pulsed to a high negative voltage. Ions in the plasma are accelerated toward the target and implanted in its surface. Working with collaborators at the University of Wisconsin and General Motors Research Laboratories, we have assembled a large-scale PSII facility at Los Alamos as part of a three-year Los Alamos/General Motors Cooperative Research and Development Agreement (CRADA). This facility uses technology originally developed for energy research and defense programs and is built around a 1.5-m-diam, 4.6-m-long cylindrical vacuum chamber with a pulse modulator capable of supplying a 60-A peak current and a 2.4-A average current at up to 120 kV. Present implants are limited by the available power supply to a 1-A average current at 50 kV, but a power supply with a 2-A average current at 150 kV is presently being installed. An upgrade to a 300-A peak current is planned. Nitrogen implantation has been performed on objects with surface areas of 4.6 m², which is significantly larger than has been achieved elsewhere, and adherent 5- μ m films of hard, low-friction carbon have been deposited on a variety of aluminum and silicon substrates. We are developing collaborations with a number of other industries involving machine-tool manufacturing and power production.

Fusion-Product Diagnostic Development for the International Thermonuclear Experimental Reactor

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Several novel fusion-product detectors with relevance to the proposed ITER are under development. A compact, 14-MeV directional neutron detector has been modeled, designed, and built for use in a high-gamma or 2.5-MeV-neutron background, which would be encountered on a large present-day, magnetic-fusion tokamak device. This detector incorporates hundreds of 0.5-mm-diam, plastic-scintillator directional (BCF-10) fibers, which are embedded in 10-cm-long aluminum blocks. The high-energy neutron is detected by observing the large light pulse generated by a knock-on recoil proton in the plastic. If the neutron path is along the fiber, the full pulse height is recorded. If the neutron is transverse to the fiber, only a small pulse is generated. Improved gamma rejection is achieved by stopping Compton electrons in the aluminum matrix so that they are not seen in the scintillator. A detector that is more insensitive to radiation damage, but still based on the same principles as above, is required for experimental work on ITER. This novel diagnostic (nicknamed the Sci-Fi detector) is a joint venture of P-1, P-14, and A-3 (now TSA-3). Testing the device with actual gamma and neutron sources has been done at the EG&G Energy Measurements, Inc., radiation test range in Las Vegas, Nevada, and on the TFTR at the Princeton Plasma Physics Laboratory in New Jersey. Preparations are being made to field multiple instruments at the large Japanese tokamak, JT-60U, located at

the Japanese Atomic Energy Research Institute in Tokai (Naka), Japan. Thin diamond detectors have been developed and built by MEE-11 (now MST-11) and are being tested as lost-alpha detectors at the Joint European Torus in England. Improved scintillators with linear response from alpha fluxes up to ITER-relevant levels have been tested at the Los Alamos Ion Beam Facility for use as lost-alpha detectors as well.

Plasma-Flow-Switch Development

F. J. Wysocki [(505) 667-6543], B. G. Anderson, R. R. Bartsch, J. F. Benage, J. C. Cochrane, F. S. Garcia, M. H. Garcia, O. F. Garcia, R. F. Gribble, J. S. Ladish, R. Newton, D. Ortega, D. J. Rodríguez, P. Roybal, G. M. Sandoval, D. W. Scudder, J. S. Shlachter, J. B. Stone (P-1)

This project is a component of the Los Alamos Athena Program, which is aimed at using pulsed-power techniques to conduct AGEXs in support of the weapons program. The ultimate goal of this project is to develop a switch that will turn an input current pulse of 10 to 60 MA (depending on the particular primary driver) that rises in 3 to 6 μ s into a current pulse that rises to full current in 300 to 500 ns. The shorter this rise time, the better. This pulse-sharpening technique is used on the existing Pegasus II capacitor bank in P-1 and on present and future explosively driven current generators developed by M-6 (now DX-15), and it will be used on the Atlas capacitor bank. One application of fast-rising, high-current pulses is to produce high-speed implosions of low-mass cylindrical metallic foils. An intense x-ray pulse is produced when the imploding foil collides on axis. We are developing a fast opening switch that prevents current from flowing through the foil until peak current is reached. This switch, known as the plasma-flow switch (PFS), was previously tested on the Pegasus I capacitor bank. This year we conducted our first PFS experiments on the Pegasus II bank, which has allowed us to study how the performance of the PFS scales with peak driver current. So far, the peak voltage developed by the PFS with a 9- to 10-MA input current (Pegasus II) is 8 to 10 times higher than the highest voltage produced by Pegasus I switches with a 5- to 6-MA input current. However, even the recently produced 80 kV is not quite high enough to drive high-quality implosions. Another factor of 2 to 4 improvement in the opened voltage is desirable. In addition to the Pegasus II experiments this year, we had a very successful Procyon explosive-generator-driven PFS test in which we examined the effects of using a different radial profile ($1/r$ versus $1/r^2$) for the mass density of the PFS. The results from this test without an imploding foil are very promising. Procyon PFS tests with imploding foils are planned for FY94.

P-2: Medium-Energy Physics

Fermilab Experiment E772: Study of the Nuclear Antiquark Sea via $p + A \rightarrow \mu^+ \mu^- X$

D. M. Alde [(505) 667-9428] (P-2, now in P-3), J. G. Boissevain, T. A. Carey, R. Jeppesen, J. S. Kapustinsky, D. W. Lane, M. J. Leitch, J. W. Lillberg, P. L. McGaughey, J. M. Moss, W. E. Sondheim, J.-C. Peng (P-2), G. T. Garvey, H. Baer (P-11), Collaborators from Abilene Christian University, the University of Chicago, Fermi National Accelerator Laboratory, the University of Illinois at Chicago, Lawrence Berkeley Laboratory, the Institute of Physics at Taiwan, Northern Illinois University, and the University of South Carolina

In Fermilab E772, a fixed-target experiment, data were collected from June 1987 through February 1988. The experiment, which far exceeded its original objectives, had several noteworthy accomplishments. It is the first high-statistics study of the A -dependence of the Drell-Yan process. Data on $p + A \rightarrow \mu^+ \mu^- X$ were measured using four heavy targets (i.e., carbon, calcium, iron, and tungsten) and a cryogenic ^2H target. The reported yields per nucleon, $R = Y_A/Y_H^2$, are accurate to better than 2% systematic error. The experiment produced the first measurement of the A -dependence of the ψ' resonance. It also produced the first significant measurement of the A -dependence of the Y family of resonances. During 1993, the group analyzed data collected during the physics run and published papers.

Fermilab Experiment E789: Study of Two-Prong Decays of Neutral B and D Mesons; Fermilab Experiment E866: Measurement of $\bar{d}(x) / \bar{u}(x)$ in the Proton

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Physicists from P-2 have played a leading role in the Fermilab E789 experiment, the original goal of which was to detect charmless B decays. The scope of the experiment has expanded to include new measurements of the nuclear dependence of J/ψ - and D -meson production. Approximately 4,000 $D \rightarrow K\pi$ and approximately 100 $B \rightarrow J/\psi X$ events are estimated to have been collected during the July 1991 through January 1992 running period of the experiment. Those data, which are now being analyzed and published, are expected to lead to important results on the nuclear dependence of D -meson production and on the B -meson cross section at 800 GeV. New data on the A -dependence of J/ψ production at negative x_F and very large x_F have been obtained. As part of their role in the experiment, the P-2 group took on the important responsibility of implementing a silicon-strip vertex detector to carry out the experiment. That detector was the first silicon-strip detector that had to operate in an experimental radiation environment similar to that expected of silicon detectors that were being built for experiments at the Superconducting Super Collider (SSC). The performance of this vertex detector was of considerable interest to teams working on the SSC. The apparatus from this experiment will be used in the recently approved Fermilab E866

experiment where the Drell-Yan process will be used to probe the $\bar{d}(x)/\bar{u}(x)$ asymmetry in the proton. The possibility of a large $\bar{d}(x)/\bar{u}(x)$ asymmetry has recently been suggested as an explanation for the apparent violation of the Gottfried sum rule observed in deep inelastic-scattering experiments.

The NA-44 Experiment at the European Center for Nuclear Research

B. V. Jacak [(505) 667-8121], J. G. Boissevain, D. E. Fields, M. J. Murray, M. Sarabura, J. E. Simon-Gillo, W. E. Sondheim, J. P. Sullivan, H. W. van Hecke (P-2), Collaborators from institutions in the United States, Denmark, Germany, Switzerland, and Japan

Experiment NA-44 at the European Center for Nuclear Research (CERN) is a second-generation, relativistic, heavy-ion experiment that focuses on distributions of identified charged particles at mid rapidity. The main thrust of the experiment is to study correlations among identical particles as a function of p_T , to provide a closer look at the space-time extent of the central region of heavy-ion collisions. The experiment is unique at 200 GeV/nucleon in its ability to compare correlations of identified pions, kaons, and eventually protons. Comparison of pion and kaon results clarifies the effects of resonance decays versus the time evolution of the emitting source. The NA-44 high statistics allow a careful study of the behavior of the (usually not well understood) chaoticity parameter and the exact shape of the correlation function. Members of the collaboration also interact with theoretical colleagues to study correlation functions predicted by the Relativistic Quantum Molecular Dynamics (RQMD) event generator and to compare those predictions with the NA-44 data. This work has provided the first detailed explanation of the information contained in the shape of the correlation function.

The PHENIX Experiment at the Brookhaven National Laboratory Relativistic Heavy Ion Collider

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Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) project presents an opportunity to increase the $\sqrt{s}$ of relativistic heavy ion collisions by a factor of 10 over the highest available energy to date and to look at systems with much larger energy densities. We are actively involved in the PHENIX collaboration, which focuses on leptons, photons, and hadrons. We believe that lepton measurements provide the most promising approach at RHIC as the leptons leave the hot, dense system relatively undisturbed by the hadronization process and the surrounding matter. Careful study of p -nucleus collisions will allow us to quantify effects of cold nuclear matter while the extension to high-mass muon pairs allows a grounding of the results by quantum chromodynamics (QCD) calculations in the q^2 region where they are understood. Our group has primary responsibility for both the silicon multiplicity and vertex detector subsystem and the muon arm subsystem of the experiment. Several Los Alamos physicists serve on the Detector and Executive Councils for PHENIX.

Experiments at the Superconducting Super Collider

W. W. Kinnison [(505) 667-4504], G. B. Mills, A. P. T. Palounek, H.-J. Ziock (P-2), M. Brooks, D. M. Lee (P-11)

Los Alamos physicists worked on the issues of silicon tracking for the SSC since before any of the experiments were accepted. They were involved, and played a major role, in both of the approved experiments: the Solenoidal Detector Collaboration (SDC) and the Gammas, Electrons, and Muons (GEM) experiment. In both cases, physicists from P-2 played a major role in defining the issues and leading engineering teams both here and at other institutions involved in the design and construction of large silicon vertex detectors, which were to be an integral part of central tracking for both of the approved experiments on the SSC. Because the major objective of the SSC program was the identification of the Higgs boson, those trackers would have been an absolutely essential ingredient in the overall physics objectives of the experiments. The experience gained in the design and development of these silicon trackers will now be available to other projects both here at Los Alamos and elsewhere.

Search for Very Rare Decays of the K_L

W. W. Kinnison [(505)667-1381], R. J. McKee, Jr., H.-J. Ziock (P-2), D. M. Lee, G. W. Hart, E. C. Milner (P-11), G. H. Sanders (ADPLS)

The decay $K_L \rightarrow \mu e$ is forbidden by the separate conservation of the additive quantum numbers associated with electron- and muon-type leptons. Observation of this decay would provide evidence for interactions outside the Standard Model of electroweak interactions, and the absence of this decay in very sensitive searches rules out various alternative theories and extensions to the Standard Model. The processes $K_L \rightarrow \mu\mu$ and $K_L \rightarrow ee$ are permitted in the Standard Model, but they are highly suppressed, flavor-changing, neutral-current decays. We searched for these decays in the recently completed experiment (E791) conducted at Brookhaven National Laboratory. Final analysis of the data gave us a new upper branching ratio limit of 3.3×10^{-11} (90% confidence level) for the reaction $K_L \rightarrow \mu e$. We also have a new upper limit for the branching ratio $K_L \rightarrow ee$ of 4.1×10^{-11} . We are currently completing the analysis of data in the $K_L \rightarrow \mu\mu$ channel where we previously published a measured branching ratio of 6.96 ± 0.40 (statistical) ± 0.22 (systematic) $\times 10^{-9}$. Simple dimensional arguments show that our sensitivity will probe mass scales on the order of 100 TeV/ c^2 for new particles that might mediate the $K_L \rightarrow \mu e$ reaction.

The L3 Experiment at the European Center for Nuclear Research

W. W. Kinnison [(505) 667-4504], J. G. Boissvain, T. E. Coan, J. S. Kapustinsky, G. B. Mills (P-2), D. M. Lee, M. Brooks (P-11), T. C. Thompson, G. B. Miller (ESA-8), the L3 Collaboration

Los Alamos has been a collaborator on the L3 experiment at the Large Electron-Positron Collider at CERN in Geneva, Switzerland, since 1990. Members of P-2 and other organizations at Los Alamos and elsewhere have recently built and installed a new silicon-microvertex detector (SMD) into the L3 detector. The SMD, which has two tracking layers and is 30-cm long and 15-cm in diameter, improves the vertex-finding capability of L3 to about a 20- μ m impact-parameter resolution and with about a 30% improvement in the momentum resolution for charged particles. The SMD also greatly improves the z-position resolution for charged particles. The primary purpose of the SMD was to ensure that L3

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would be in a position to improve the limits on the Higgs mass when the beam energy of the machine goes up to 200 GeV $\sqrt{s}$ in the next couple of years. In the meantime, the SMD will allow L3 to carry out a very aggressive program of B -meson and τ -lepton physics. The Los Alamos role in the SMD was to provide the front-end read-out electronics and final system integration.

Alternating-Gradient Synchrotron Experiment E890: Test of Charge Symmetry in η Production on Deuterium

M. J. Leitch [(505) 667-5481], J.-C. Peng, D. M. Jansen (P-2), M. Clajus, B. M. K. Nefkens, J. W. Price, W. B. Tippens, M. J. Wang, D. B. White (University of California, Los Angeles), S. Bart, R. E. Chrien, P. H. Pile, R. Sawafte, R. J. Sutter (Brookhaven National Laboratory), H. Seyfarth (Forschungszentrum Jülich), I. Slaus, A. Svarc, M. Batinic (Ruder Boskovic Institute)

This recently approved experiment first took data at the Brookhaven National Laboratory Alternating-Gradient Synchrotron (AGS) in the summer of this year. The experiment measures η mesons produced in the $\pi^+d \rightarrow nn\eta$ and $\pi^+d \rightarrow pp\eta$ reactions. A comparison of the differential cross sections for the two reactions provides a direct test of charge symmetry. Violation of charge symmetry could be caused by π^0 - η mixing. Another goal of the experiment is to measure the dependence on energy and angle of the $\pi^+d \rightarrow pp\eta$ differential cross section. This experiment could have practical applications since the $\pi^+d \rightarrow pp\eta$ reaction is being considered as the η -meson production reaction of a new AGS η -meson factory. Los Alamos has played a major role in the experiment in that one member of P-2 is a co-spokesperson for the collaboration, and a major ingredient of the apparatus is the η -meson spectrometer, which was originally built by P-2 for experiments that were conducted at the Los Alamos Meson Physics Facility (LAMPF).

Research and Development of the Superconducting Super Collider Tracking System for the Gamma, Electron, and Muon Collaboration

G. B. Mills [(505) 665-5510] (P-2), S. F. Hahn, B. J. Cooke (NIS-11)

The integrated research and development project culminated in a working design of a radiation-hardened, high-bandwidth, data-acquisition system for a silicon-microstrip tracking system that was to be a part of the GEM experiment at the SSC laboratory. The GEM experiment was designed to investigate the spontaneous breaking of electroweak symmetry at energy scales of 1 TeV. The design requirements imposed by the SSC operational and environmental conditions made the tracker design a challenging effort. The electronics needed to be sensitive to small signal sizes of 24,000 electrons from the solid-state silicon-microstrip detectors, had to meet the high 60-MHz clock-cycle time of the SSC, and had to achieve less than 1-mW power dissipation per channel. Moreover, the large number signals from the 2,500,000 individual channels in the system needed to be compressed to a manageable form for transmission off of the tracker device. The entire system must survive a total lifetime radiation dose of 3 Mrad. The modular design includes a very-large-scale-integration chip set consisting of ten 128-channel analog circuits for signal amplification and discrimination, ten 128-channel complementary-metal-oxide-semiconductor digital chips for data buffering and compression, and a fiber-optic link to transmit data off of the device.

Background Radiation and Activation of Superconducting Super Collider Detectors

A. P. T. Palounek [(505) 665-2574], H.-J. Ziock (P-2), J. Comly, H. G. Hughes, H. Lichtenstein, R. E. Prael, L. S. Waters (X-6), T. L. Tally, W. B. Wilson (T-2)

Detector design for modern accelerators must address radiation issues, including induced radioactivity, radiation damage, and neutron and gamma background rates in detectors. Induced radioactivity raises concerns about detector performance, component lifetime, radiation hazards to personnel, conditions of personnel access, detector maintenance, and component disposal. We used a series of codes to calculate the neutron and gamma backgrounds in SSC detectors and the production and decay of radionuclides in the detectors, beamline components, and the detector hall. Our calculations showed unexpectedly high levels of background rates in some sections of the detector, prompting a redesign of the detector shielding in which we were also involved. We used the high-energy particle generation code (DTUJET) to simulate primary minimum-bias interactions and the Los Alamos high-energy transport (LAHET) code system, together with the low-energy MCNP transport code, to follow the subsequent reactions in the detector, in beamline components, and in the detector halls. The CINDER'90 nuclide inventory code then used the irradiation history, material compositions, residual nuclide yields, and neutron fluxes from the Monte Carlo calculations to perform the transmutation calculations and provide activation results. Finally, based on the results from CINDER'90, we used MCNP to compute biological-dose equivalent rates. We also developed the capability to track particles through a magnetic field for LAHET. The code series developed for these calculations has already proved useful in other accelerator applications and has helped promote Los Alamos expertise in background and activation calculations.

Characterization of a Neutral Particle Beam for the Ground Test Accelerator Project

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Our team was responsible for measuring the properties of the expanded neutral particle beam that would have been produced by the Ground Test Accelerator. For this task, we employed the pinhole method. Working closely with ESA-6 and ESA-8, we designed a large-scale vacuum enclosure for the accelerated H⁻ beam with two major functions. The pinhole plate station with low-duty-factor beam stop was to be located on the upstream end. Here the incoming H⁻ beam, about 40 cm in diameter, would have been converted into a rectilinear array of 1-mm-diam outgoing neutral beamlets. The detector chamber would have been located downstream at a distance of 30 m, and it would have contained two advanced imaging systems based on charge-coupled devices (CCDs). The image data were to be processed on-line by computer to provide information about the beam on an individual pulse basis. The principle of the method was successfully demonstrated at the Argonne National Laboratory linear accelerator several years ago. Our experimental method allowed precision measurements of steering focus, geometric

aberrations, chromatic aberrations, microscopic divergence, and momentum spread. During the last year, our efforts focused on producing documentation and publications of results from previous years when we did detailed studies of the apparatus that was to be used in the design.

Radiation-Hardness Studies of Silicon *p-i-n* Detectors

H.-J. Ziock [(505)667-7265], K. Holzscheiter, A. P. T. Palounek (P-2)

The next generation of colliding-beam and fixed-target experiments will require tracking detector systems that have extremely good position resolution ($\sim 10\ \mu\text{m}$) and good time resolution ($\sim 20\ \text{ns}$) and will survive fluences on the order of 10^{14} particles/cm². Silicon detectors provide both the required position- and time-resolution capabilities. We have investigated their tolerance to large particle fluences using the beams available at LAMPF. To maintain the required signal-to-noise characteristics in high-fluence applications, we have determined that the detectors must be operated close to 0°C . We have characterized the radiation-induced change of doping concentration in the *i*-layer of the *p-i-n* structure. That doping concentration is directly proportional to the full-depletion voltage required to operate the detectors. We find that the *i*-layer, which for our samples was actually initially very lightly doped *n*-type silicon, gradually changes to *p*-type material during the irradiation. That process involves at least two effects: (1) the destruction of the initial donor sites responsible for the initial *n*-doping and (2) the creation of acceptor sites from the bulk material. The required full-depletion voltage decreases rapidly following the radiation exposure (i.e., the annealing stage). During that time, some of the newly created acceptor sites decay back to neutral sites. A longer period follows in which the depletion voltage remains approximately constant. We discovered that, at still later times, an anti-annealing effect becomes visible. During the annealing stage, the depletion voltage increases with time and eventually surpasses the value it had when the detector was removed from the beam. We have determined the time constants associated with both the annealing and anti-annealing processes. We found that the values of those constants are very strong functions of temperature, and we determined that functional relation. Our results will play an important role in determining the use of, and operating conditions for, silicon detectors in future high-fluence applications.

Research and Development of the Solenoidal Detector Collaboration Silicon Tracking System

H.-J. Ziock [(505)667-7265], A. P. T. Palounek (P-2), W. O. E. Miller, W. Christensen, G. D. Dransfield, C. Grastataro, J. A. Hanlon, F. D. Michaud (ESA-8), K. A. Woloshun (ESA-13), J. Williams (MST-7)

We were responsible for the mechanical systems design of the silicon tracking system (STS) for the SDC experiment, one of two major experiments that was planned for the SSC. That responsibility included the support structures, the cooling system, the electrical distribution system, and the overall integration of the silicon system. The STS was to be over 5 m in length and 1 m in diameter, and it needed to be supplied with several thousand amps of current. The system generated over 10 kW of waste heat and had to be operated near 0°C . The stability of the system had to be maintained at a $5\text{-}\mu\text{m}$ level. The material inventory had to be limited to very small amounts of low-Z materials to keep the radiation length of the silicon system to about 10% of one radiation

P-3: Subatomic Research and Applications

length. The system had to withstand integrated radiation doses of about 5 Mrad. We developed novel design concepts, special materials, and new diagnostic instrumentation. Some of the developments included thin, high-strength composite materials with enhanced thermal conductivities; a very low mass evaporative cooling system, which essentially provided isothermal operation; and a laser television holography system needed to resolve micron-scale changes in dimension of large (~ meter scale) objects in real time and over extended periods (days). Much of what we learned and developed can be applied to other large silicon detector systems such as those planned for the upgrade of the experiments at Fermilab or for the Large Hadron Collider to be built at CERN.

Status of the Russian-American Gallium Experiment

T. J. Bowles [(505) 667-3937] (P-3)

The "solar neutrino problem," whereby the observed flux of high-energy solar neutrinos is a factor of 2 to 4 below that predicted by the Standard Solar Model (SSM), has been around for 20 years. Possible sources of the solar neutrino problem include astrophysical explanations or explanations that require invoking new physics, such as neutrino oscillations. The extreme temperature dependence (T_c^{18}) of the flux of high-energy ^8B neutrinos has precluded a definitive conclusion. The radiochemical solar-neutrino experiments that use gallium are predominantly sensitive to the low-energy p-p solar neutrinos. The p-p neutrinos are produced by the primary energy-producing reaction in the Sun, and their flux is directly related to the observed solar luminosity and is insensitive to variations in the solar models. The Russian-American gallium experiment (SAGE) is measuring solar neutrinos with metallic gallium at the Baksan Neutrino Observatory in southern Russia to try to determine the origin of the solar neutrino problem. SAGE began operation in 1989; first results were announced in 1990. The initial results, based on five months of data with 30 tons of gallium, indicated a strong suppression of the solar neutrino flux but with large uncertainties. Our published result was $20 \pm 15/-20$ (statistical) ± 32 (systematic) solar-neutrino units (SNU), compared with the SSM prediction of 132 SNU. This low result generated great interest in the scientific community, as well as with the popular press. Because there were large uncertainties in the measurement, we upgraded SAGE in 1991 to improve sensitivity. The series of tests that were carried out showed no unexpected losses of the ^{71}Ge atoms, which were formed by the solar neutrinos. In the summer of 1991, SAGE began data collection again but with 57 tons of gallium and backgrounds 40% lower than those reported in 1990. The data from an additional test-run period of six months in 1991 combined with the 1990 data gave a result of $58 \pm 17/-24 \pm 14$ SNU. This result is somewhat lower than, but in reasonable agreement with, the GALLEX result of $87 \pm 14 \pm 7$ SNU. We are completing the analysis of additional runs in 1992 and expect to announce new results from SAGE shortly. The present results of both the gallium experiments now favor Mikheyev-Smirnov-Wolfenstein (MSW) neutrino oscillations as the source of the solar neutrino problem. However, before one can make any strong claims for new physics from the gallium experiments, both SAGE and GALLEX need to accumulate more data with better signal to background and to carry out full-scale calibrations using an intense ^{51}Cr neutrino source. During 1992, we further upgraded the SAGE counting systems so that we could also count the L-peak (at 1.2 keV); this upgrade nearly doubled our counting efficiency. The SAGE team is also working on preparations for a

full-scale ^{51}Cr calibration experiment, which is scheduled for fall 1994. Thus, we hope by the end of 1994 to have completed the calibration runs and to have collected sufficient data with a high signal to background to be able to make a strong statement about the source of the solar neutrino problem.

Redetermination of the Newtonian Gravitational Constant

G. G. Luther [(505) 667-3178], C. H. Bagley (P-3)

The strength of the gravitational force, first described by Newton, determines the motion of galaxies and planets, the light output of the sun, and how fast an apple falls. The strength of this force is being measured in an abandoned flash-x-ray bunker at the end of Frijoles Mesa in Los Alamos. In this experiment, two 10-cm-diam tungsten spheres, each weighing 10 kg, are rotated about a small dumbbell-like torsion pendulum, which is enclosed in a long, cylindrical vacuum chamber. The fine quartz fiber (approximately $7\text{ }\mu\text{m}$ in diameter) supports the torsion pendulum and allows it to respond to the change in position of the tungsten spheres as they rotate. A knowledge of the distribution of the masses, and the change thereof, allows the determination of the strength of the gravitational force between the torsion pendulum and the masses. Amazingly, the force measured in this table-top-sized experiment is the same as the force that holds galaxies together. The experimental site, which is 1,000 ft above the Rio Grande River, was chosen because it is away from two disturbing influences: traffic and the change in the level of the water table.

Sonoluminescence

G. G. Luther [(505) 667-3178], J. S. Nico (P-3)

Sonoluminescence, first examined by Lord Rayleigh, is still not clearly understood. A propagating sound wave in a liquid can sometimes excite a shock wave in a bubble and cause it to emit light. This light closely resembles that of a black body at very high temperatures (no one knows exactly how high) for very short times (no one knows exactly how short). The apparatus in which the sonoluminescent bubble is induced consists of a 250-ml spherical glass flask filled with distilled water. Seven piezo-electric sonic transducers are affixed to the flask at symmetrically distributed points and driven in phase so as to induce a breathing mode in the flask. A sound wave propagates radially toward the center of the water-filled sphere, and a luminous bubble forms at the center of the spherical flask. The small 10- μm bubble glows with a blue light for less than 100 ps on each cycle of the sound wave. The goal of the present investigation is to determine the color temperature and duration of this light pulse.

Elastic Backscattering Lidar for a Miniature Seeker Technology Integration Satellite

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An elastic backscattering lidar (**L**ight **D**etection **A**nd **R**anging) is being designed for the Ballistic Missile Defense Organization to fly on a Miniature Seeker Technology Integration (MSTI) satellite in low-earth orbit. The 100-kg payload features a 76-cm-diam, primary-light-collection mirror and a diode-pumped Nd:YAG laser (1064 nm) that emits 1.5 J per pulse at a repetition frequency of 50 Hz. The telescope, fixed with respect to the satellite, has a 6° field-of-regard, within which a scanning mirror will select the laser beam direction and the field-of-view of 0.5 mrad. Other payload elements are the detector (avalanche photodiode) and the R3081-microprocessor-based payload control electronics. The primary goal is to track a theater missile from space and to generate a track file that can be handed over to a kinetic kill vehicle. In addition, dual-use potential for ecological monitoring will be demonstrated. The missile would be acquired through a succession of passive, active exhaust plume, and active hard-body signals. However, there are very few measurements of the backscattering properties of missile exhausts. As we are especially interested in the scattering return for an Aries missile exhaust, we have taken a ground-based lidar system to the White Sands Missile Range and observed an Aries launch at a range of 7 km. Measurements were made at 1.06 and 0.53 μm wavelengths simultaneously. The lidar was calibrated by scattering the laser beam from a Lambertian target board. The Aries volume backscatter coefficient at 1.06 μm was $0.015 \text{ m}^{-1} \text{ sr}^{-1}$. The Aries exhaust is thus easily observable from space for the MSTI lidar parameters. The calculated backscatter coefficient was in the range of 0.0021 to $0.013 \text{ m}^{-1} \text{ sr}^{-1}$, depending on the phase of the aluminum oxide and the size distribution of the particles.

Autonomous-legged Robot Research

M. W. Tilden [(505) 667-2902] (P-3)

Coping with unstructured environments is one of the main challenges of modern robotics. The idea of cheap, autonomous, all-terrain vehicles to carry sensors or to do unsupervised work is an old, unfulfilled dream. However, the work being done in the P-3 evolutionary robotics lab is tackling this problem head on with a series of processor-free robots using emergent properties of nonlinear systems to control actions in lieu of algorithms. So far, several capable "bugs" have been constructed by the use of adaptive analog networks inside of compliant, robot frames. Future efforts will be concentrated on the development of more efficient and capable "species" of robots and on how users can "trick" these robots to use their inherent self-preservation sense to reliably perform long-term tasks from mine sweeping to biochemistry. Once general principles for building such devices are finalized, machines may be custom fit to applications where even the user is uncertain about the work environment.

Neutron Time-Reversal Violation*J. F. Wilkerson [(505) 667-9429] (P-3)*

Measurement of the triple correlation (between neutron spin, electron momentum, and proton recoil) in neutron beta decay provides an excellent method to search for possible time-reversal invariance violation (TRIV). The goal of such a measurement is to shed some light on the long-standing charge-conjugation parity (CP) violation puzzle. The neutron triple-correlation measurement is sensitive to a number of theories that predict observable TRIV effects: left-right symmetric, leptoquark, and exotic fermion-physics models. Of equal importance, free neutron decay is relatively insensitive to processes that mimic TRIV. Groups from the University of California, Berkeley; the University of Michigan; and the National Institute of Standards and Technology (NIST) have joined with our P-3 Weak Interactions Group to form the EMIT collaboration to search for TRIV in neutron beta decay. We propose to measure the neutron triple-correlation coefficient to a sensitivity of 3×10^{-4} , an improvement of nearly an order of magnitude over previous measurements. The measurement will be made by observing the protons and electrons produced from the beta decay of free neutrons, which will be provided by the NIST Cold Neutron Research Facility in Gaithersburg, Maryland. The detector will consist of four electron-sensitive detector segments and four proton-sensitive detector segments arranged in an alternating octagonal geometry. The proton segments will consist of p-i-n diode detectors enclosed in an electrostatic accelerating structure. The electron segments will be plastic scintillators. The selection of an octagonal geometry was chosen on the basis of Monte Carlo studies that predict increased sensitivity equivalent to a factor of 7 greater beam flux compared with a geometry with similar detectors oriented at 90° . We carried out a highly successful proof-of-principle test run at NIST in the spring and summer of 1992. This run verified our Monte Carlo simulation predictions and allowed us to test our proposed proton detector segment, to examine possible electron detection methods, and to study room- and beam-related backgrounds. Design of the full experiment is well under way. Polarized measurements with the complete detector will be done in 1995.

Thin-Wall Imaging (1): Laser-Aiming Studies*D. A. Baker [(505) 665-6671] (P-4)*

Data were obtained as a part of the precision Nova-pointing studies (i.e., the Nova laser at Lawrence Livermore National Laboratory). The objective was to obtain measurements in hohlraum geometry by viewing individual laser footprints through thin-walled targets. The three-dimensional nature of the cylindrical targets led to the development of computer analysis codes, which calculate the location of laser-footprint centroids on the cylindrical hohlraum starting from the planar x-ray-film images obtained with x-ray pinhole cameras. These calculations made use of the images of fiducial markers on the targets and the aiming and location coordinates of the diagnostic. The laser-footprint locations are then used to compute the mean-axial positions of a pair of five-beam ring locations and the standard deviations of the individual laser footprints from each of these mean-ring locations. Sensitivity studies showed that errors in diagnostic aiming can affect these calculated results (i.e., about $10 \mu\text{m}$ per degree of aiming error for the ring locations). An important conclusion from this work is that the uncertainties in diagnostic aiming

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relative to the target can be reduced by using many fiducials. Then the input aiming variables of the analysis code for the diagnostic are varied until a least-squares minimum is obtained in the deviations of the calculated fiducial positions from the preshot target metrology. This type of study can be automated by coupling an image-target mapping code to a least-squares, nonlinear, optimizer routine. In this way, statistical-error averaging can be exploited. In a recent experiment on aiming accuracy, we obtained mean-beam-ring deviations and standard deviations of laser footprints of less than 30 μm . A preliminary check, which was done by irradiating one side of a thin, gold, flat target, was made to compare the hard x-ray images taken through the gold with softer x-ray images on the laser-incident side. The resulting images were not greatly different. The result lends credibility to this technique for determining laser-beam aiming in hohlraum geometry.

Thin-Wall Imaging (2): Time Dependence of Laser-Energy Deposition Regions

D. A. Baker [(505) 665-6671] (P-4)

Gated x-ray images obtained using thin-wall hohlraums show the time dependence of laser footprints. The images diffuse as time progresses. How well the thin-wall, hard-x-ray images track the locations of regions of spectrally softer internal x-ray sources is an important interpretation question. LASNEX (Los Alamos ICF design code) calculations have indicated that the hard-x-ray images taken through the wall do not depart too far from the calculated locations of the laser-energy deposition region. The LASNEX simulations for thin-wall studies have also helped predict results that have been used in setting up experimental parameters. The calculations predict that for pulse lengths used in these experiments to date, wall breakup before the fusion-fuel capsule reaches maximum compression is not expected. A study examining longer laser pulses is planned.

Thin-Wall Imaging (3): Capsule Implosions

D. A. Baker [(505) 665-6671] (P-4)

A limited number of full-capsule implosion shots were made using thin-wall hohlraums. The integrated-pinhole-camera images obtained showed both the laser-beam footprints and the imploded capsule, whereas the gated-x-ray-camera images showed the time history. For all shots at 2.5 kJ per beam with 1-ns square pulses, the neutron yield was 10^9 or greater. These high yields give evidence that the thin-wall hohlraum does not greatly degrade the quality of the implosion. Further work is needed to explore the longer pulses of primary importance to the ICF indirect-drive program. Obtaining good implosions for long laser pulse lengths may require thicker gold walls than previously reported (see Chapter III, Project Descriptions, *Thin-Wall Imaging (1): Laser-Aiming Studies*, page 101, and *Thin-Wall Imaging (2): Time Dependence of Laser-Energy Deposition Regions*, page 102). Past studies have shown that we can obtain useful images by increasing the thickness of the gold walls by at least a factor of 2.

Basic-Image-Analysis Experiment

N. D. Delamater [(505) 667-7946], D. B. Harris (X-1), A. Hauer (P-4)

The basic-image-analysis experiment was designed with the goal of understanding the formation of the observed x-ray images of imploded capsules that are used as signatures of drive symmetry in a hohlraum. The experiment has applications to areas in both the Hydrodynamically Equivalent Physics Program and the Hohlraum Plasma Physics Program because it will aid our understanding of the basic hydrodynamics of capsule implosions and of x-ray emission and absorption that occur in imploded capsules. The experimental series used deuterium-filled capsules, with or without argon, and CH shells, with or without chlorine in the innermost layer. Many previous Nova shots had used capsules doped with chlorine as a diagnostic for mix. Addition of chlorine in this manner is responsible for both self-emission and absorption of the argon emission from the core. The goal of these experiments is to assess the importance of the effect to the implosion core imaging as a symmetry diagnostic. Time-integrated and time-gated images of capsule implosions were obtained and comparisons were made of image shape and brightness for a number of capsules with or without argon in the gas and with or without chlorine in the shell. We conclude that the presence of the chlorine in the shell yields a small but measurable effect on the observed x-ray-image shape and brightness. We also see much brighter images than predicted for deuterium-filled capsules without argon—that is, the calculated ratio of argon to no argon capsule emission is much larger than observed. Whether the code overestimates the core emission or underestimates the shell emission is yet to be determined. Further work is under way to absolutely measure the imploded-capsule emission using an accurate x-ray film calibration and pinhole camera data and also using CCD camera images of implosions. These results will be important in understanding the discrepancies between data and code results.

Spatially Discriminating Optical Streaked Spectrograph

J. A. Cobble [(505) 667-8290] (P-4)

SDOSS, the spatially discriminating optical streaked spectrograph, is a Nova diagnostic instrument designed for sampling a laser-plasma environment with spatial resolution, spectral resolution, and temporal resolution. Spatial resolution is accomplished by imaging the laser target with a Cassegrain telescope onto an intermediate focal plane where a field stop provides spatial discrimination. A typical aperture diameter is one-sixteenth of an inch, which with 8x magnification of the telescope gives data integrated over only about 200 μm . This discrimination allows, for example, the collection of scattered light from a beam at a particular radius of a hohlraum target. Transmitted light is focused onto the slit of a 0.25-m spectrograph where spectral resolution is obtained. The spectral coverage, depending on the grating setting, extends for 6,000 $\text{\AA}$ in the range from 2,000 to 12,000 $\text{\AA}$. Therefore, a number of parametric plasma instabilities can be examined, including stimulated Brillouin scattering (SBS) at the laser-drive wavelength λ_0 , stimulated Raman scattering (SRS) from λ_0 to $2\lambda_0$, and two-plasmon decay with its signature at $2/3\lambda_0$. With the S-1 photocathode response of the streak tube, SDOSS is prepared to function with either 2ω or 3ω drive at Nova. Spectral resolution is modest, at about 20 $\text{\AA}$ per pixel on the CCD camera readout, but it permits determination of plasma-electron density from SRS and electron temperature from the SRS low-wavelength cutoff or from the splitting of the $2/3\lambda_0$ signal. Additionally, relative amplitudes can be compared for

target-dependent measurements, e.g., empty versus gas-filled hohlraums. The streak tube provides the temporal resolution. Temporal windows of about 30, 12, 6, 3, and 1.2 ns dispersed over 480 pixels are available. The system is being fitted with an optical fiducial for temporal and spectral calibration.

P-6: Biophysics

Kinetic X-ray Crystallography on Carbonmonooxy Myoglobin

J. R. Berendzen [(505) 665-2552] (P-6), I. Schlichting (Max Planck Institute for Medical Research, Heidelberg, Germany)

The oxygen-storage protein myoglobin (Mb) has become the prime model system for physical studies of the relation between molecular structure and biological function. Mb reversibly binds O₂, CO, and other small ligands at its heme iron. Absorption of a photon causes the ligand to dissociate, and the subsequent rebinding reaction may be followed with time. We are combining two approaches, kinetic spectroscopic measurements and x-ray diffraction techniques, to address the structure-function problem and to identify in detail the motions that take place during the sequence of ligand rebinding in Mb. Kinetic spectroscopic measurements on Mb have been used to learn a great deal about the dynamics of the molecule, and x-ray diffraction techniques have given us its three-dimensional structure at high resolution. The results bear on the more general problems of allostery and control in proteins and the techniques developed in the course of this work are applicable to a broad range of kinetic problems in structural biology. We have completed the design and construction of an x-ray diffraction camera for use with Laue diffraction at cryogenic temperatures. We have tested it at the Stanford Synchrotron Radiation Laboratory and the National Synchrotron Light Source (NSLS). Using the camera, we optimized flash-freezing conditions for the Mb crystals and demonstrated that protein crystals can be flash frozen and retain the very high degree of crystalline order needed for Laue diffraction. In the process, we obtained the first high-quality, high-resolution diffraction patterns of a protein crystal at liquid-helium temperatures. Analysis with the Daresbury Laue program suite shows that the flash-frozen crystals diffract to better than 1.9 Å. The water coordinated to the heme can readily be seen in electron-density maps, which were calculated from a room-temperature Laue data set with phases taken from monochromatic data. We soon hope to have similar data showing changes in Mb structure after photolysis of carbon monoxide ligands.

Weak Field Sensor Project

E. R. Flynn [(505) 667-4746], P. J. Kung, W. C. Overton, Jr., P. F. Ruminer, D. van Hulsteyn (P-6)

The development of a large biomagnetic sensor for the National Institutes of Health is the principal focus of this project. The goal is to construct a 93-sensor system capable of covering the entire human head. The dewar, which will contain the sensor system, has been designed and placed out for bid by potential subcontractors. A design for the sensor coils has also been completed and will be integrated with the Superconducting QUantum Interference Devices (SQUIDS). These will be constructed by CONDUCTUS, Inc., a leading superconducting electronics company. Design of the coil forms and the data-acquisition system are in progress. A CRADA has been established with CONDUCTUS to develop generic, SQUID-based, weak-field sensors for a variety of applications,

including biomagnetic sensors. The initial effort in this direction is to build a 12-sensor system based on a flat-plate geometry. This sensor system will be used (1) to test the limits of the imaging-surface concept, (2) to examine the function of such a sensor system for magnetocardiography, and (3) to begin the investigation of such systems for nondestructive evaluation purposes. In No. 3, materials with known surface defects and corrosion will be examined by this sensor system to test its ability to detect and locate such magnetic anomalies. Finally, an extensive analysis of sensor-system parameters and how they affect resolving power was accomplished by using a chi-squared approach for defining resolution for two sources and by using the criterion to determine the effect of parameter variation (e.g., coil spacing and size, as well as gradiometer baseline and types of gradiometers) on system resolution. This theoretical approach will be followed by a phantom study in which two dipoles that can be moved relative to each other in a saline solution with high precision will be used. The results of this experimental study will be compared with the theoretical study and will be used for various instruments under development.

Strategies for Source Space Limitation in Neuromagnetic Inverse Procedures

J. S. George [(505) 665-2550], H. A. Schlitt, C. C. Wood (P-6), P. S. Lewis (ESA-6)

The use of magnetic recordings for localization of neural activity requires the solution of an ill-posed inverse problem—that is, the determination of the location, spatial configuration, strength, and time course of the currents that give rise to a particular observed field distribution. Inverse procedures that produce distributed estimates of neuronal currents have received increasing attention because they do not require *a priori* estimates of model order and parameter values, they are suitable for automated analyses, and they allow localization of sources that are not point-like. To combat the parameter explosion and the resulting underdetermination associated with distributed reconstruction, we have explored both algorithmic and knowledge-based strategies to limit the effective reconstruction space: variable resolution hierarchical models; anatomical constraints on the reconstruction volume; iterative procedures that effectively eliminate putative source locations that are not relevant to the specific reconstruction, such as the FOCUSS (FOCal Underdetermined System Solution) algorithm; and methods that consider an evolving subspace of the reconstruction volume. We have recently achieved encouraging results by explicitly limiting the reconstruction space at each step so that the inverse problem is always well conditioned. Using a genetic algorithm, we specify a number of distinct subsets of the full reconstruction space using strings consisting of ones and zeros. At each step, a metric is evaluated for the best linear reconstruction over the subspace specified by each string. Depending on this measure of “fitness,” the string is either retained or removed from the evolving population of strings. New strings are produced by piecewise recombination of older strings. Under some conditions new “genetic material” is introduced into the population by stochastic processes. Genetic algorithms appear to hold particular promise for the neuromagnetic inverse problem because once a suitable subspace configuration has evolved to account for some domain within the target solution, this configuration will tend to be preserved and combined with other partial solutions.

Anatomically Realistic Head Models for Functional Brain Imaging with Electroencephalography and Magnetoencephalography

L. Heller [(505) 665-3057], H. A. Schlitt, D. M. Ranken (P-6), R. Aaron (Boston University), E. D. Best (C-6)

The inverse problem for electroencephalography and magnetoencephalography (MEG) is an attempt to infer neuronal currents in the brain from surface electric and magnetic measurements, respectively. A necessary first step in this process is the solution of the forward problem—namely, calculating the electric potential and magnetic-field distributions produced by any assumed neuronal current. For the widely used spherical model of the head, there are analytic formulas for these quantities. But for an anatomically realistic model of the head, one must solve numerically for the “return” currents that flow in the electrically conducting medium consisting of the brain, skull, and scalp. We implement such calculations by solving a boundary integral equation for the electrical potential on all the surfaces where there are significant discontinuities in electrical conductivity. This work involves setting up triangulated meshes, derived from magnetic resonance imaging (MRI) scans, on these conductivity boundaries. By comparing the numerical solutions with those of analytic formulas in the spherical case, we have validated the accuracy and smoothness of the procedure as a function of mesh size and location of the neuronal current. We now have a reliable method for solving the equation. This method is practical for use in the inverse problem, and we are applying it to actual MEG and MEG data.

Electrophoretic Velocities of Single Molecules

E. B. Shera [(505) 667-3228], A. Castro, M. V. Peters (P-6)

We have developed a technique for the electrophoretic separation and identification of single molecules. The electrophoretic velocities of individual molecules in solution under an applied electric field are measured. Single molecules are subsequently identified by comparing them with the electrophoretic velocity characteristic of a particular molecular species. An electric field is applied between the ends of a capillary cell, which causes the molecules to migrate. The individual molecules are detected as they pass through each of two laser beams. The electrophoretic velocity is then calculated from the time required for each molecule to travel the distance between the two beams. The technique has been successfully demonstrated for the identification of nucleic acids and proteins. The single-molecule sensitivity of the technique is many orders of magnitude greater than that of conventional methods, and it represents an enormous step in the effort for enhancing the sensitivity of analytical instruments. It promises to bring a new array of capabilities to many areas of science and technology, from biochemical analysis of clinical samples to the detection of trace environmental contaminants.

Imaging of Magnetic Fields Using a Superconducting Spherical Sensor Array

D. van Hulsteyn [(505) 667-0825], W. C. Overton, Jr., E. R. Flynn (P-6), A. G. Petschek (P-DO)

Electric currents in the vicinity of a superconductor induce currents on the superconducting surface. If the surface is a sphere or a large plane, the induced currents can be represented by equivalent images. A sensing loop placed parallel to the surface will detect a signal from both the source and its image; the combined signal in the case of a planar surface is exactly the same as that measured by a first-order gradiometer. The original theoretical analysis of this problem was performed by treating currents as charges in motion. This approach, which is valid for the planar case, does not apply for curved surfaces. In order to extend this theoretical analysis to the spherical case, we have expressed the currents in terms of electrical and magnetic multipoles. Because the divergence of current is zero, we show that current components tangential to the surface contribute only to the magnetic sources. Similarly, radial currents contribute only to electric sources. The associated electric field must first be obtained to determine how radial currents affect the magnetic field. Thus, one must use the dynamic equations to obtain the magnetic field produced by radially oriented currents even though the currents do not vary in time. To our knowledge, the solution obtained in this manner is new. More important, it provides a more generally applicable means for representing the superconducting imaging problem in a variety of surface geometries. These results are directly applicable to P-6's Weak Field Sensor Project (see Chapter III, Project Descriptions, *Weak Field Sensor Project*, page 104).

Photoemission Spectroscopy Using Synchrotron Radiation

A. J. Arko [(505) 667-0758], J. J. Joyce, R. I. R. Blyth, A. B. Andrews, J. D. Thompson (P-10, now MST-10), Z. Fisk (CMS), R. J. Bartlett (P-14)

We are using angle-resolved photoemission spectroscopy to study the electronic structure of two important classes of compounds: high- T_c superconductors and heavy-fermion systems. Photoemission measurements yield information about the nature and energy position of the electronic states in a material. Angle-resolved measurements can actually map out the energy versus momentum dispersion. We have developed what we believe is one of the world's most sensitive spectrometers (capable of better than 20-meV resolution) with which we can accurately study the line shapes of high- T_c spectra in the presence of a superconducting gap. The same high resolution also allows us to study heavy-fermion systems in which a narrow resonance at the Fermi energy may be responsible for the unusual behavior of these systems. Understanding the origin and role of this resonance is important for a microscopic interpretation of heavy-fermion phenomena.

Nonlinear Thermal Physics

R. E. Ecke [(505) 667-6733], N. Li (P-10, now MST-10)

We are exploring general properties of nonlinear systems in model-fluid experiments. Nonlinear dynamics and chaos are investigated in a small cell of liquid ^3He -superfluid ^4He , which is forced to convect by the application of a vertical temperature gradient. The formation of patterns and the dynamic mechanisms for the selection of pattern wavelengths are

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studied in large cells with many convection rolls. Rotation about a vertical axis imposes Coriolis and centrifugal forces on the thermally convecting fluid and strongly influences the pattern dynamics. Localized vortex structures can form into a stable lattice and then destabilize as the heating is increased; turbulent convection is thereby produced. These model systems provide laboratory examples of general problems in many disciplines, including materials science (e.g., dendritic growth and directional solidification) and geophysical fluid dynamics (e.g., thermal convection plus rotation controls atmospheric circulation).

Novel Materials

Z. Fisk [(505) 665-0892] (CMS), D. G. Mandrus, J. D. Thompson (P-10, now MST-10)

In the physics of metallic conductors, much interest centers on materials in which electron-electron correlation effects are large. In such systems, one can find heavy-fermion compounds, various kinds of magnetic materials, and all the materials classed with high- T_c oxides. The properties of such materials are of both fundamental and applied importance. We investigate the physics of such materials by varying the parameters of the materials (e.g., stoichiometry, elemental composition). The search for new materials with structures related to those with known, interesting properties can enhance these properties and can provide insight into their microscopic origins.

Magnetic Resonance

P. C. Hammel [(505) 665-0759], A. P. Reyes, E. T. Ahrens (P-10, now MST-10), R. H. Heffner (P-DO)

The magnetic-resonance program employs the techniques of nuclear magnetic resonance (NMR) and muon spin resonance (μ SR) as means of probing the electron dynamics and structural properties of a variety of novel electronic materials. We have recently focused on studies of the novel magnetic and superconducting properties of high- T_c cuprates and heavy-fermion materials. With NMR, we can microscopically probe behavior separately at the various sites in a crystalline lattice. Nuclear-resonance frequency shifts resulting from hyperfine fields, which arise from the polarization of electronic spins, provide information about local electronic susceptibility and the symmetry of the responsible electronic orbitals. We can obtain local structural information by studying the electric field gradient at a site of interest. Fluctuations of the local field resulting from electronic spins cause the relaxation of nuclear spins. Thus measurements of the relaxation rate of nuclear spins provides information about dynamical properties of electrons, including the density of states at the Fermi surface. Unlike NMR, μ SR is sensitive to magnetic behavior at interstitial sites in a lattice. Spin-polarized muons are implanted by an accelerator, and the decay of the polarization is detected by measuring the spatial asymmetry of the emitted positron from the weak, parity-violating decay of the muon.

Inertial Confinement Fusion Program

J. K. Hoffer [(505) 667-4049], (P-10, now MST-10), L. R. Foreman (MST-7), J. D. Simpson, J. B. Gibson, N. B. Alexander (General Atomics)

Cryogenics will play a vital role in the future of the National Inertial Confinement Fusion Program. The high starting density of D-T fusion fuel afforded by cryogenic condensation inside the target shell allows one to carry out the implosion along a lower adiabat, resulting in the desired final density at lower drive energies. The redistribution of the cryogenic fuel to a discrete, uniform, high-density solid shell occurs naturally below 19 K because of a phenomenon known as "beta layering" and results in an additional substantial gain in implosion efficiency. However, uncertainties as to the exact thickness and density homogeneity of the beta-layered D-T shell must first be resolved. Furthermore, the interior surface of the D-T solid shell must be sufficiently smooth to prevent undesired instabilities during the laser-driven implosion. We are actively investigating these topics using a variety of physical techniques, including optics, ultrasonics, neutron scattering, and NMR.

Flux Noise Characterization of High- T_c Superconductors

M. F. Hundley [(505) 667-4129], J. D. Thompson, M. P. Maley (P-10, now MST-10)

Our goal is to improve our understanding of the physical processes and mechanisms involved in fluxoid dynamics in high- T_c superconductors. The critical current density, which determines the technological usefulness of these materials, is controlled by the interplay between fluxoid motion and pinning, which determine fluxoid dynamics. We are working to improve our understanding of these phenomena by measuring the flux-flow noise, which is the frequency-dependent voltage noise produced when an applied current forces a superconductor into its dissipative regime above J_c . The amplitude, frequency, magnetic-field, electric-field, and temperature dependencies of the incoherent, low-amplitude, flux-flow noise are all fundamental functions of the physical processes involved in fluxoid dynamics. A detailed study of these physical dependencies allows us to better understand the unique superconducting state exhibited by the highly anisotropic high- T_c materials and to further Los Alamos efforts toward improving their potential for use in technological applications.

X-ray and Neutron Scattering Studies of High- T_c and Heavy-Fermion Materials

G. H. Kwei [(505) 667-8840], S. Billinge (P-10, now MST-10)

X-ray and neutron-scattering techniques together constitute an extremely powerful probe of high- T_c superconductors and heavy-fermion materials. The objective of our research program is to use these techniques to elucidate the role that crystal and electronic structures play in the behavior of these unique materials. For high- T_c superconductors, major areas of interest include oxygen stoichiometry and defect structure, cation ordering, copper valence, static and dynamic disordering, and the morphology of the different phases. We will use conventional and anomalous x-ray and neutron scattering techniques to study the structures of superconducting materials. Structural problems include structural characterization; studies of oxygen stoichiometry and cation ordering; and the study of changes in structure with temperature, pressure, composition, and processing conditions. The techniques used

include x-ray and neutron powder diffraction, single-crystal neutron diffraction, small-angle neutron diffraction, and inelastic neutron scattering. For heavy-fermion materials, we have been concerned primarily with neutron diffraction studies of structural phase transitions and magnetic ordering. We are now embarking on a program to investigate valence transitions in heavy-fermion systems by using anomalous x-ray scattering, which probes the local electronic structure of these systems.

Resonant Ultrasound Spectroscopy of High- T_c Materials

A. Migliori [(505) 667-2515], D. G. Mandrus, T. W. Darling (P-10, now MST-10), Z. Fisk (CMS), W. M. Visscher (T-11)

We have developed resonant ultrasound spectroscopy as a fundamental thermodynamic and transport probe for use with single crystals too small to be studied using any other ultrasound technique. Our system and software permit a signal-to-noise ratio 6 orders of magnitude better than that of previous resonance techniques used to probe the elastic properties of solids. This technique is being applied to study unusual elastic behavior in high- T_c superconductors and related materials. The improved accuracy has enabled us to accurately track attenuation effects in metal hydrides and in metallic glasses down to 4 K and to re-examine the $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ structural phase transition for which we developed specific predictions for the behavior of all the moduli and then measured them. Nondestructive testing, using the technique of resonant ultrasound, offers a number of potential applications that are of interest to the United States Air Force and several industrial corporations.

Electronic Transport in Quantum Dots

R. Movshovich [(505) 667-4799], R. E. Ecke, J. D. Thompson (P-10, now MST-10), D. L. G. Smith (MST-11)

When an electron's motion is spatially confined to dimensions comparable with, or smaller than, the natural length scale (the de Broglie wavelength) that governs its quantum mechanics, quantum size effects become pronounced. With the advent of modern semiconductor-fabrication techniques, electron confinement to as low as zero dimensions can be realized in quantum dots, which are formed by sandwiching, for example, GaInAs between layers of GaAlAs, with overall structural dimensions of much less than 1 μm . The current-voltage characteristics of such a structure, which can be highly nonlinear, may permit the fabrication of extremely high-frequency oscillators or fast-sampling circuits. We are studying the electrical properties of quantum-confined systems to understand the complex interplay between atom-like effects and collective many-body effects in these structures. Eventually, the unique properties of quantum-confined systems may be useful in applications involving new information processing and telecommunications.

Novel Heat Engines and Heat Pumps

G. W. Swift [(505) 665-0640] (P-10, now MST-10)

We are exploring novel heat-engine technology by establishing basic physical and design principles through experimentation and analysis. The program includes the use of liquids near the critical point as working fluids in heat engines and heat pumps as an alternative to Freon-based air conditioners, refrigerators, etc.; the use of acoustic technology to

eliminate moving parts and sliding seals in reciprocating heat engines and heat pumps; and the use of ^3He -superfluid ^4He mixtures as working fluids in zero-gravity sub-Kelvin cryocoolers.

Mössbauer Spectroscopy

R. D. Taylor [(505) 667-4729] (P-10, now MST-10), M. P. Pasternak (Tel Aviv University)

The Mössbauer effect is a nuclear physics tool that allows detailed studies of solid-state properties at a microscopic level. These properties include valence, magnetism, phase transitions, mixed phases, and lattice dynamics. By using diamond-anvil-cell techniques, we are performing Mössbauer effect experiments on selected systems at hydrostatic pressures to 660 kbar at temperatures to 0.02 K. Recent work has centered on pressure-induced transitions, such as molecular crystal-metallic-amorphous transformations and metallic and magnetic transformations in the Mott insulators: NiI_2 , CoI_2 , and FeI_2 . The Mössbauer effect also provides unique information on local environment changes with doping and with oxygenation in a number of high- T_c superconducting materials.

Ion-Beam Materials Laboratory

J. R. Tesmer [(505) 667-6370] (P-10, now MST-10)

The Ion-Beam Materials Laboratory is a facility for characterizing and modifying materials with ion beams. Rutherford backscattering and ion-beam channeling are two popular techniques used by Laboratory researchers to characterize thin films, such as epitaxially grown layers and high- T_c thin-film superconductors. Other projects include radiation-damage research and a wide range of tribological studies. We also have programs in the areas of microbeam analysis by particle-induced x-ray emission and nuclear-resonance gamma-ray absorption. The Ion-Beam Materials Laboratory is operated by P-10 (now MST-10) and is sponsored by the Center for Materials Science. Users come from within and outside the Laboratory.

Materials at Ambient and Extreme Conditions

J. D. Thompson [(505) 667-6416], M. F. Hundley, R. Movshovich, T. Graf, J. Neumeier (P-10, now MST-10), Z. Fisk (CMS)

We use thermodynamic, transport, and magnetic measurements at ambient and extreme conditions of very low temperatures, high pressures, and high magnetic fields to understand the essential physics of novel materials. Research focuses on materials, such as heavy-fermion systems, cuprates, and fullerene-based compounds in which electron-electron interactions play a significant role in determining their properties. Ambient-environment studies are used to discover new phenomena, to guide the discovery of new materials, and to assess the need for further in-depth microscopic studies, whereas measurements under extreme conditions permit an investigation of a material's response to extremes in thermodynamic variables without perturbing lattice periodicity or chemical purity. Together these measurements give a broad view of how the physics of novel materials should be described and bridge the gap between materials synthesis and microscopic understanding.

P-14: Fast-Transient Plasma Physics

Photoabsorption and Compton Scattering in the Double to Single Photoionization Ratio of Helium

R. J. Bartlett [(505) 667-5923] (P-14), M. Sagurton (SFA), J. A. R. Samson (University of Nebraska)

Double photoionization in helium is of interest because the ejection of the second (shake-off) electron results from its correlation with the primary electron through the electron-electron interaction. Thus, calculations of the cross section for double photoionization are good tests of electron-correlation models in atoms. Most theoretical studies have only considered the photoabsorption process. These studies predict a high-energy asymptotic limit of the ratio, $R(h\nu)$, of the double-photoionization to single-photoionization cross sections of 1.66%. Previous measurements of $R(h\nu)$ have found an asymptotic limit near 1.5%. We have measured $R(h\nu)$ between 2.1 and 5.5 keV and have found two distinct trends in the data. For $h\nu$ between 2.1 and 3.8 keV, the data are consistent with an asymptotic limit of 1.66%. Above ~ 3.8 keV, we observed a fall off in $R(h\nu)$, which we attributed to increased He^+ production that resulted from the onset of ionizing Compton scattering. The effect of Compton scattering on $R(h\nu)$ can be approximately described with a simple model, which makes use of the Klein-Nishina Compton-scattering cross section for free electrons and the constraint that the energy transferred to the $\text{He}(1s)$ electron must be greater than the ionization potential.

Optical Constants from Reflectivity Measurements at Synchrotrons

R. L. Blake [(505) 667-7369 or (516) 282-2838] (P-14), Collaborators from the Harvard/Smithsonian Center for Astrophysics, Brigham Young University, and Lawrence Berkeley Laboratory

An improved reflection technique has been introduced to permit more accurate measurements of material optical constants d and β , the density r , and from these the atomic scattering factors f' and f'' . Regions of normal and anomalous dispersion can be measured with a resolving power of 1,000 or larger using a portable reflectometer test station (RTS) that is moved to any appropriate synchrotron beamline, particularly the four Los Alamos beamlines at the NSLS. The RTS has been refined over the past three years. The technique involves fitting the Fresnel equations to measured reflectivity versus angle for any material that can be deposited as a thin, uniform layer on a flat superpolished substrate. Both the real and imaginary parts of the complex optical constants of materials may be derived. High-quality results have been obtained on the L-edge region of nickel (800 to 1,100 eV); the L-edge region of molybdenum (2,000 to 3,000 eV); and the M-edge region of iridium, platinum, and gold (2,000 to 3,500 eV). Optical constants d were not previously measured for iridium, platinum, gold, and molybdenum. From these measurements, we also established a real difference (~ 40 eV) between the x-ray spectroscopic edges M_V and M_{IV} and the electron-spectroscopy binding energies for iridium, platinum, and gold.

Precision Spectroscopy Program

R. L. Blake [(505) 667-7369 or (516) 282-2838], M. P. Hockaday, D. V. Morgan (P-14), N. S. P. King, M. D. Wilke (P-15), Collaborators from New Mexico State University

Since 1983, P-14 and P-15 have been involved in a precision-spectroscopy program. Results from the Correo and Panchuela events at the NTS showed the value of high-resolution atomic spectroscopy in diagnostics of hot plasmas created by these events. We are developing a state-of-the-art, precision, double-crystal spectrometer to improve the accuracy of x-ray atomic spectra throughout the periodic table as part of our support of the NTS and AGEX programs. This spectrometer will function as a vacuum- or air-operated instrument with automated scanning and parameter optimization. It can provide (from a single instrument with crystals referenced to a silicon standard) a consistent set of the inner-shell atomic spectra of all elements with an accuracy of 1 ppm. Improved-accuracy spectral tables will benefit several physical sciences whenever calibration standards are needed. The instrument has been prepared for operation by colleagues and students at New Mexico State University (NMSU). Special high-purity silicon boules have been transferred to NMSU for processing. This year, data were taken in Bragg geometry (reflection) and Laue geometry (transmission) from quartz crystals that will be used in future NTS and AGEX spectroscopic diagnostics. The system worked as designed. It revealed residual bending in our thin quartz samples.

Synchrotron Activities

R. L. Blake [(505) 667-7369 or (516) 282-2838], R. G. Hockaday, G. C. Idzorek (P-14), Collaborators from Lawrence Berkeley Laboratory, the Smithsonian Astrophysical Observatory, and EG&G Energy Measurements, Inc.

Four endeavors were pursued on the four Los Alamos x-ray beamlines at the NSLS: (1) beamline development, (2) beamline characterization, (3) calibration-program measurements, and (4) research on the optical constants of materials. Beamline development included commissioning tasks on beamline U3A, mechanical improvements to the beamline X8A, and additions to the beamline software for expanded applications. Beamline characterization involved measuring the flux, harmonic content, and scattered light from the X8A and X8C beamlines. Upon studying the properties of the first mirrors on beamlines U3A and U3C, we found some defocusing problems and inhomogeneities on both beamlines. A corrective mirror design has been planned for U3A. Calibration measurements were carried out on beamlines X8A and X8C over the energy range 0.26 to 20 keV and U3C from 0.1 to 1.5 keV. The real-time system introduced last year has permitted calibrations of detectors that agree, within a few percent, with conventional source calibrations from EG&G Energy Measurements, Inc. Two people from EG&G have been stationed at NSLS to support the calibration activities. They have developed a routine in which they conduct calibration operations on each of three beamlines every four months (the NSLS scheduling period). Also they established an x-ray laboratory in a building adjacent to the synchrotron where they placed x-ray systems formerly used at EG&G Las Vegas Operations. The fourth endeavor, research on optical constants, is reported in this publication as a separate project description (see Chapter III, Project Descriptions, *Optical Constants from Reflectivity Measurements at Synchrotrons*, page 112).

Mid-Z to High-Z Opacity Research

M. Y. Hockaday [(505) 667-0070], R. L. Blake, P. J. Walsh (P-14), B. H. Wilde (X-2)

We are developing techniques to measure the continuum opacity of mid-Z elements at indirect-drive temperatures on the Nova laser at Lawrence Livermore National Laboratory. With point-projection spectroscopy, the spectrum of a backlighter created by two Nova laser beams is passed through a sample, which is heated inside a hohlraum by eight Nova beams, and then onto a bent crystal from which it is dispersed onto a detector. Refinements carried out over the past two years have led us to use niobium samples for measurement of L- and M-shell continuum and line opacities in the 1- to 3-keV range. Time-integrated data taken on x-ray film were used to establish the technique and develop refinements by comparing data with model calculations. A time-resolved measurement is needed to achieve opacity accuracy approaching our goals. This measurement is now being implemented by means of a time-gated microchannel-plate detector.

Heated X-ray Fluorescer Studies

G. C. Idzorek [(505) 667-8848] (P-14), R. G. Hockaday (P-4), W. Matuska (X-5)

To observe extremely intense x-ray sources without instantly destroying the detector, one can use a fluorescer foil, which is illuminated by the source, and then place a detector shielded from the source to observe the fluorescent x-rays emitted from the foil. During the experiment, the fluorescer foil is ionized. This process may cause changes in the fluorescent yield of the foil and may consequently change the system-response calibration of the fluorescer/detector combination. Fluorescent-yield experiments done on the Saturn pulsed-power machine at Sandia National Laboratories produced inconclusive results. Studies are currently under way to determine if the Los Alamos Pegasus II pulsed-power x-ray source can be used to detect carbon-fluorescent-yield changes in thin plastic films.

Pegasus II Pulsed-Power Experiments

G. C. Idzorek [(505) 667-8848], W. C. Coulter (P-14), R. G. Hockaday (P-4), T. A. Ortiz (P-1)

We are fielding a number of x-ray diagnostics on the Pegasus II pulsed-power machine located at TA-35. A time-integrated, four-image, filtered x-ray pinhole camera provides spatial information on the implosion. Filtered x-ray diode arrays provide time-resolved x-ray output for several different x-ray energies from 6 eV to 10 keV. A transmission-grating spectrometer (TGS) provides time and spectrally resolved data from 60 eV to 2 keV with 5-ns time resolution. Currently, the data from a number of diagnostics arrayed perpendicular to the implosion axis are being correlated to study the uniformity and output of the source. The results are being used to benchmark the implosion calculating codes, observe effects of machine modifications, and determine the suitability of the source for experimental programs.

Russian Pulsed-Power Experiments at Angara-5

G. C. Idzorek [(505) 667-8848] (P-14), R. G. Hockaday (P-4), Collaborators from EG&G Energy Measurements, Inc.

An experiment involving Russian scientists and Los Alamos, Sandia, and Lawrence Livermore National Laboratories was performed at the Russian pulsed-power laboratory, Angara-5, which is located at the Trinit Laboratory in Troitsk, Russia. Los Alamos fielded a TGS to provide time and spectrally resolved information about imploding cylindrical liners from a series of 31 shots performed in June 1993. The TGS system provided data from 60 eV to 2 keV with a 1-ns time resolution. Analyzed data show a semi-Planckian spectrum with an implosion peak temperature of about 85 eV. Complementary diagnostic systems were fielded as a joint effort between the Russian Laboratory and the Los Alamos, Sandia, and Lawrence Livermore National Laboratories.

X-ray Detector Calibration Program

G. C. Idzorek [(505) 667-8848], R. G. Hockaday (P-14), Collaborators from EG&G Energy Measurements, Inc.

P-14 has several vacuum-ultraviolet and x-ray beamlines at the NSLS located at Brookhaven National Laboratory. These beamlines provide monochromatic photon beams between about 30 eV to 20 keV. Two EG&G staff members are stationed at NSLS to support our detector-calibration program, which provides calibrated detectors that are used for x-ray measurements at the NTS, on the Los Alamos Pegasus II and Procyon pulsed-power machines, on the Saturn pulsed-power machine at Sandia National Laboratories, on the Nova laser at Lawrence Livermore National Laboratory, and at other facilities. The EG&G team maintains a set of calibration standards that cover the range from vacuum-ultraviolet to 50-keV photon energies. Specialized hardware and software enables the team to provide routine calibrations for our normal diagnostic detectors. The detector is shipped to team members at NSLS where they perform the calibration, and then the detector and the calibration report are shipped back to Los Alamos. For unique detector configurations, the EG&G team provides their expertise and equipment to assist scientists in their calibrations.

Energy Selective Reaction History

G. L. Stradling [(505) 667-8334] (P-14), Collaborators from EG&G Energy Measurements, Inc.

Working with EG&G Las Vegas Operations and Santa Barbara Operations, we have designed and fabricated a low-resolution magnetic filter for high-energy electrons in the 10- to 25-MeV range. Discrimination against lower-energy electrons (1 to 4 MeV) provides a method of examining D-T burn in the presence of significant fission emission. This apparatus was designed to satisfy the requirements of 1-MeV discrimination across the energy range of interest while sampling across the 1-MeV energy band to prevent aliasing in the data. We have built the necessary apparatus, using an existing magnet. We ran an experiment with the energy-selective-reaction-history apparatus at EG&G Santa Barbara Operations and mapped out the dispersion and beam-broadening characteristics of the magnet. At that point, the programmatic imperative for continuing calibration of the experiment evaporated. Consequently, the apparatus has been mothballed until it is needed again.

Fast Charge-Coupled-Device Camera

G. L. Stradling [(505) 667-8334] (P-14), Collaborators from EG&G Energy Measurements, Inc.

With EG&G Los Alamos Operations, we are continuing with the development of a millisecond read-out camera. We have proceeded with the testing and characterization of a CCD chip obtained in the first run from the foundry, Loral. Although this chip is defective in two characteristics (because of production errors), it demonstrates that the technology we designed into the chip is viable. We have imaged several of the panels of this sixteen-panel device and have successfully operated the chip at 20 MHz. We have negotiated the terms for a second run with Loral and only await the resources to pay for the run. The development of the custom camera electronics to run the Loral Fairchild CCD chip is proceeding at a reduced pace because funding has delayed the acquisition of fully functioning CCD chips. A breadboard camera has been completed, and a prototype camera is in fabrication. We have determined a method of extending the unique CCD design of this chip into a sixteen-panel framing camera with a 20-ns shutter time and independently short interframe times. A modest design change and an additional chip run will be required.

X-ray Phase Optics

G. L. Stradling [(505) 667-8334] (P-14), Collaborators from Brigham Young University and MOXTEK

With Brigham Young University and MOXTEK, we are evaluating the technology of manufacturing stepped, x-ray-reflective surfaces for the fabrication of x-ray-phase gratings. This technology has the potential for the fabrication of versatile x-ray-phase optics, which have application in analytic x-ray-metrology instrumentation, x-ray microscopy, x-ray-projection lithography, and nanofabrication. We are fabricating two-level surfaces with multilayer x-ray-reflective structures coated on both levels. The reflective characteristics and surface smoothness of these samples will be measured at the Los Alamos synchrotron beamlines at the NSLS and with Los Alamos atomic-force microscopes.

P-15: Applied Physics Experiments and Imaging Measurements

Magic Lantern Adaptation Project

K. L. Albright [(505) 667-1184], G. J. Yates (P-15)

During the calendar year 1993, Group P-15 continued to develop a special-purpose camera as a component in a military system that detects mines in the surf zone of the ocean and on beaches. The system concept is to scan an area with a pulsed laser, image reflected light onto the matrix of a CCD, generate a digital electrical signal representative of the image, and transmit the signal to a station for object identification. Ultimately, an operational frame rate of a few thousand frames per second is desired. The camera produces the electrical signal so that the platform may move at typical jet aircraft speeds. P-15 has assembled a camera known as the GY-5. During 1993, the GY-5 camera was calibrated and operated at conventional television rates in a "tank test" conducted by the United States Navy in Santa Barbara, California. The test consisted of forming images in light transmitted through a tank of sea water with different conditions of depth, purity, and turbulence. Ongoing activities will

include an operation described as a "pier test," whereby objects will be placed in a shallow part of the ocean planned for either Andros Island (Bahamas) and San Clemente, California, in 1994. An improved camera, called the GY-6, will be used in the pier test.

Medical Applications for High-Speed Video

F. H. Cverna [(505) 667-1533], K. L. Albright, S. A. Jaramillo, V. H. Holmes, N. S. P. King, G. J. Yates (P-15)

P-15 originally designed and evaluated high-speed focus projection and scan (FPS) vidicon and CCD cameras to meet the requirements for imaging diagnostics in support of the underground nuclear test program at NTS. P-15 has recently found new applications for this technology, most notably in medical x-ray imaging. Experimental work, which began in late FY93 as a Laboratory-Directed Research and Development project, used P-15's high-speed video systems and x-ray equipment from WX-3 (now ESA-2) to demonstrate and calibrate 500- to 700-frame-per-second video that showed objects being x-rayed. The video systems were used in experiments with the x-ray and image-analysis systems at the Henry Ford Health System's Bone and Joint Center/Motion Analysis Laboratory to show the feasibility of "human-motion-analysis" studies involving dynamic joint loading and range of movement. Proposals for further collaborative work have been developed.

Explosion Effects Physics Project

R. E. Hill [(505) 667-8754] (P-15)

This project carries out work for the Department of Energy (DOE) Office of Nonproliferation and National Security through programs administered by the Nonproliferation and International Security Division at Los Alamos. At the present time, the project has two major areas of responsibilities: (1) conducting research and development in support of verification requirements of the treaties limiting nuclear testing and (2) maintaining the capability for the United States to verify the Threshold Test Ban Treaty (TTBT) by use of on-site hydrodynamic yield measurements (CORTEX). As the negotiations now under way for a multilateral Comprehensive Test Ban Treaty (CTBT) make progress, requirements to maintain readiness for TTBT verification are expected to decrease. The project is therefore being refocused on research and development activities related to monitoring subsurface nuclear explosions in the context of a CTBT. As a multidisciplinary effort, these research and development activities will involve (1) field experiments, such as the recently completed nonproliferation experiment at the NTS, to study the influence of source conditions on seismic signals from underground explosions; (2) laboratory experiments and theory to study the influence of material properties on stress-wave propagation in geological media; and (3) large-scale computations to numerically simulate subsurface explosions and carry out parametric studies. The goal of these research and development activities is to provide a basis for developing algorithms that can be applied to seismic- and hydroacoustic-monitoring data to help identify and characterize nuclear explosions.

Technology Demonstrations

S. A. Jaramillo [(505) 667-3466], K. L. Albright, G. J. Yates, T. E. McDonald (P-15)

Group P-15 exhibited design instrumentation at two industrial conferences during the reporting period. The first was at Hill Air Force Base, Ogden, Utah, where the audience for camera hardware exhibits and Los Alamos capabilities was principally Air Force personnel and contractors. The second was the Armed Forces Communications and Electronics Association (AFCEA) West Conference in San Diego where both the FPS and CCD intensified, shuttered cameras were operationally demonstrated at high frame rates and fast shutter speeds. A presentation of the general capabilities of P-15 was made at the AFCEA. Other technology-transfer activities include presentations of two papers at the AFCEA East Conference, which resulted in a visit by members of an interested industrial company, and a paper presented at an optical workshop held in Rochester, New York. P-15 also demonstrated high-speed imaging technology at the Laboratory's 50th anniversary exposition.

Electrostatically Focused Microchannel-Plate Image Intensifier

N. S. P. King [(505) 667-4415], G. J. Yates, S. A. Jaramillo (P-15)

An electrostatically focused microchannel-plate image intensifier (MCP-II), designed by P-15 and made by Photec, Inc., of the United Kingdom and EG&G Energy Measurements, Inc., Woburn, Massachusetts, was characterized. The MCP-II comprises a 40-mm photocathode (S-20); a fine-pitch, wire-mesh gate grid; minifying and focusing electrodes; a 30-mm microchannel plate; and a 30-mm phosphor (P-20). We measured the MCP-II's linearity, nongated and fast-gated resolution, and gating time. The gate pulse was coupled to the grid, which is located 50 mils behind the photocathode with an impedance-matched microstrip transmission line. The MCP-II's demagnification was 1.5x. For illumination via a single-mode fiber of about 8- μ m-diam input at 670 nm, 10 ns full width, half maximum (FWHM), the MCP-II saturated at input energy densities above 1.5 μ J/cm². The -3dB modulation-transfer-function (MTF) nongated resolution is 7 line pairs per millimeter (lp/mm) and the -13 dB MTF (limiting) resolution is 15 lp/mm. The shutter time was measured to be 1.6 ns (off-on-off) with a 40-V reverse bias and a 750-ps (FWHM), 800-V gate pulse. The MCP-II design (combined with the microstrip-transmission-line technique for gating) represents an approximately tenfold increase in gating speeds for a large-area intensifier with conservation of resolution.

Support of the National Center for Advanced Information Component Manufacturing

T. E. McDonald [(505) 665-7294] (P-15)

P-15 is supporting the National Center for Advanced Information Component Manufacturing (NCAICM) through project management. NCAICM was established for a period of two years by congressional action in the FY93 Defense Appropriations Bill. As a teaming effort among Los Alamos, Lawrence Livermore, and Sandia National Laboratories and industry, NCAICM is tasked with the development of manufacturing technologies in microelectronics and flat-panel displays and is focused on improving United States competitiveness in these two critical technological areas. Funding for the center and projects is

administered through the Advanced Research Project Agency (ARPA). The center also marks a new avenue of collaboration between the DOE and the ARPA. NCAICM provides a viable channel to ARPA for the transfer of existing Department of Defense (DoD) and DOE research to commercial applications and the development of dual-use technology that will benefit both DoD and DOE. Of the \$60 million approved for the center's first two years of operation, Sandia National Laboratories received \$12 million to operate the center and fund precompetitive projects (Phase I). The remaining \$48 million is devoted to projects that are carried out by partnerships between industry and the national laboratories (Phase II). The participants of these Phase II projects can have protected-technology property rights. Twenty such projects have already been funded. NCAICM was formerly opened with a workshop for potential laboratory and industry participants. The workshop was held in Albuquerque, New Mexico, and was attended by almost 400 representatives from industry, government agencies, and universities. P-Division personnel exhibited examples of P-15 work in areas that overlap microelectronics and flat-panel-display technologies.

Measurement of Neutron-induced Gamma-ray Production

G. L. Morgan [(505) 667-1137], N. S. P. King (P-15)

Gamma-rays produced by neutron bombardment of a close-in converter material can provide a means of studying time profiles for fusion reactions without the time dispersion associated with neutron energy distributions resulting from Doppler broadening. Comparisons with calculations of both gamma-ray signal strengths and time profiles associated with the neutron energy distribution depend on a detailed knowledge of the neutron-induced gamma-ray production in the converter. We have undertaken a series of laboratory experiments to provide data to test both the evaluated cross-section sets for converter materials and the accuracy of calculated predictions of gamma-rays from practical converters. This work is being carried out at the Weapons Neutron Research (WNR) Facility using the white neutron source produced from a spallation target under bombardment by the 800-MeV proton beam from LAMPF. This neutron source is used with time-of-flight (TOF) and pulse-height-unfolding techniques to determine gamma-ray spectra between 1 and 20 MeV for neutron energies between the threshold for inelastic scattering and 20 MeV. Data are obtained for scattering angles of 90°, 125°, 135°, and 149°. To date, measurements have been made on carbon samples and on four different thicknesses of beryllium oxide. The carbon data have been reduced to cross sections and compared with the evaluated data files as a means of verifying the experimental technique. The beryllium oxygen samples ranged from those thin enough for good quality cross-section measurements to those with a thickness of a proposed converter for an actual application. These data are currently being analyzed.

Target Benchmark Studies of Accelerator Transmutation of Nuclear Waste

G. L. Morgan [(505) 667-1137] (P-15)

Neutron production in four prototypical target configurations for accelerator-based conversion systems has been measured. The experiment was performed at the WNR Facility at LAMPF and was a joint project involving P and other Divisions. The targets included a solid lead target, a composite tungsten target, and a thorium-salt

composite target, each of which was bombarded with 800-MeV protons. A solid lithium target bombarded with a 400-MeV incident proton beam was also studied. Each target was surrounded with a 60-cm-diam-by-2.5-m-long blanket of solid lead. The total neutron production was studied with the manganese-bath technique. A 25-m-diam-by-3-m-long tank, which surrounds the target-blanket assembly and contains water with 1% manganese sulfate, is used for the bath. In addition, neutron leakage at angles of 7.5°, 30°, 60°, and 150° with respect to the incident proton beam was measured over the neutron energy range from 100 keV to 800 MeV using TOF techniques with flight paths ranging from 30 to 60 m. The integrated proton beam incident on the targets was measured using the activation of an aluminum foil placed in the beam ahead of the target. A gated, intensified imaging system with a phosphor screen was used to record the position and intensity of the proton beam on the face of the target. Results from the manganese activation have an uncertainty of about 7% and are in good agreement with the results of calculations using the LAHET code system. The leakage data are currently being analyzed and will also be compared with LAHET calculations.

Charge Coupled Device Workshop

G. J. Yates [(505) 667-7529], K. L. Albright, T. E. McDonald (P-15)

P-15 sponsored a high-speed video workshop in April 1993. Participants in the workshop included research scientists and engineers from Los Alamos; the United States Army Research Laboratory; the United States Air Force Wright Laboratory Armament Directorate; the United States Navy Coastal Systems Station; the Naval Research Center; the Naval Weapons Center, China Lake; the University of Arizona Optical Sciences Center; Lawrence Berkeley Laboratory; and the Atomic Weapons Establishment (AWE) of the United Kingdom. The focus of the meeting was to find out what present and future projects each group was addressing for high-speed video applications. An effort was made to find common interests and requirements that might result in jointly funded development. A letter of intent to collaborate was drafted by the group as an interim step with the goal of establishing a more formal memorandum of understanding for future joint efforts. This letter has formed the basis for several joint CCD characterization projects centered around P-15's Solid State Imager Test Station. These projects have involved P-15, the United States Air Force, the United States Army, the United States Navy, and the AWE.

High-Speed-Camera Development

G. J. Yates [(505) 667-7529], K. L. Albright (P-15)

The GY camera series of interline-transfer CCD cameras with Loral Fairchild 380 x 244 pixel imagers provides high-speed video for underground nuclear tests at the NTS. The latest cameras in this series, the GY-6 and GY-7, will perform up to 750 frames per second because of new drive electronics and new analog signal processing. Many of these new features were incorporated in the Solid State Imager Test Station for clocking imagers up to 100-MHz pixel frequencies. The GY-7, a compact quad-head version of the GY-6, allows four simultaneous or sequentially gated images to be captured for an effective 3,000-frame-per-second imaging capability. A new compact camera system is being developed for a new full-frame-transfer CCD manufactured by English Electric Valve (EEV), a company from the United Kingdom. This imager is capable of 4,000 frames per second and has an imaging area arranged in 512 x 512

pixels, but it is subdivided into eight sections of 128×256 pixels each. When each section is clocked in parallel, eight simultaneous video outputs result. Each output will include a high-speed, 10-bit, analog-to-digital converter, and the digital output of the camera will be connected to recording/playback equipment via a fiber-optic transmitting system. The approval of a joint DOE and DoD block funding proposal initiated the development of a 4,000-frame-per-second, intensified, shuttered camera, which will address "dual-use," technology-transfer initiatives. This camera will be used by Los Alamos for AGEX experiments and by the DoD for feasibility studies involving the United States Air Force Wright Laboratory Armament Directorate.

Microstrip Design for Fast Gating of Stripline Microchannel-Plate Image Intensifiers

G. J. Yates [(505) 667-7529], S. A. Jaramillo (P-15)

The goal of this project is to develop a way to shutter 18-mm MCPs on and off in less than 300 ps. The electrical gate pulse must be coupled into the MCP without suffering dispersion or reflection to achieve this goal. A high-bandwidth transmission line was designed to inject the gate pulse into the MCP with impedance-transforming microstrip configuration. Microstrip lines with dual impedance segments were designed to match the $50\text{-}\Omega$ source impedance of the gate pulse generator with the $5\text{-}\Omega$ characteristic impedance of the MCP. The microstrip line that connects the $50\text{-}\Omega$ source to the $5\text{-}\Omega$ MCP input junction is in the shape of an exponential taper with a rounded corner at the low-impedance end. The conventional MCP design was modified to provide strip transmission line (stripline) geometry with low-inductance planar tabs to interface with the microstrip lines. Fabrication of the microstrip lines has been completed. Sub-nanosecond shuttering with this design was verified in preliminary tests of the ITT (International Telephone and Telegraph) and Philips Components prototype stripline MCPs.

Phosphor Reciprocity Measurements

G. J. Yates [(505) 667-7529], S. A. Jaramillo (P-15)

Cerenkov light from a piece of Suprasil, irradiated by 16-MeV electrons from a linear accelerator, was coupled into a proximity-focused MCP. The output optical power from the MCP's phosphor was measured as a function of the input pulse width and total energy. The energy and pulse width of the light from the Suprasil were monitored with a 2-in. photodiode. The measurements were made at a variety of excitation pulse widths (50 ps, 10 ns, 15 ns, and 65 ns) and with amplitudes of constant energy-time integral, or appropriately normalized. No change was observed in the MCP sensitivity as a function of excitation pulse width. We initially conclude that there is no P-20 reciprocity failure over the range measured (50 ps to 65 ns) outside of experimental error. In future experiments, we will use ionizing radiation to directly excite the phosphor to further study reciprocity issues.

Radiation Sensitivity of Video Imagers

G. J. Yates [(505) 667-7529] (P-15)

Several solid-state imagers were characterized as to their sensitivity to high-energy photons and neutrons. Responsivities—that is, the magnitude or amplitude of video voltage generated for a known absorbed radiation dose from irradiation with 2- to 12-MeV bremsstrahlung x-ray and gamma-ray photons and 14-MeV neutrons—were determined and used as a measure of radiation hardness of CCDs and charge-injection devices (CIDs) deployed in radiation environments. Typically, experimental equipment is configured for the indirect imaging of flux by radiation-to-visible-light conversion (i.e., with the imager shielded from the source but not from scattered components of the incident flux). Charge dumping was therefore characterized to clear radiation-induced charge before the imagers were exposed to visible light from the converters. Thresholds for permanent damage resulting from accumulated doses in the kilorad to megarad range were also determined. Two commercial manufacturers contacted P-15 and requested assistance in characterizing imagers, both standard and radiation-hardened versions. The requests are in the category of Technology Transfer/Industrial Partnership initiatives—an area of interest to P-15. A Small Business Innovative Research agreement has been initiated with CID Technologies, Inc., and an informal arrangement has been established with EEV.

Test Station Projects

G. J. Yates [(505) 667-7529], K. L. Albright (P-15)

P-15's newly developed Solid State Imager Test Station is being used for the fast clocking of several new-generation CCD imagers. Los Alamos is currently submitting a patent application for this unique PC-based, programmable, high-speed test system. The system can provide parallel-signal generation at clock frequencies of up to 100 MHz, and it provides up to 48 individual digital outputs coupled to analog-delay and level-shifting circuitry of up to ± 10 V for each output. In addition, analog-processing electronics provide precise optimization of output signals. The system includes multichannel high-speed digitizers; display and processing software; and a variety of variable-wavelength, pulsed-light sources, including lasers and strobe lights. Pursuant to the collaboration initiatives formulated at the Charge Coupled Device Workshop sponsored by P-15 in April 1993, a joint effort with the United States Air Force Wright Laboratory Armament Directorate and P-15 was created, and tests are now being conducted on a newly developed EG&G, Inc., Reticon imager. This imager offers some novel features that make it a candidate for a high-resolution (512×512 pixels), high-speed (greater than 1,000 frames per second) camera. A second joint effort is under way with the same United States Air Force group and the United States Army in the testing of a newly developed back-thinned CCD from the David Sarnoff Laboratories. This sensor has potential applications in synthetic aperture radar, military tracking and surveillance, and medical imaging by virtue of its improved quantum efficiency. A third collaborative project involves the testing of a CCD developed by the AWE and EEV for a new high-speed camera that will be used for AGEX (see Chapter III, Project Descriptions, *High-Speed-Camera Development*, page 120).

Fission and Statistical Model Physics

A. Gavron [(505) 667-5475], J. P. Lestone, C. Zoeller (P-17)

The experiment to measure neutron emission in the $^{238}\text{U}(n,f)$ reaction at WNR is now complete, and the data are being analyzed. At this time, we have obtained the mass-yield and total-kinetic-energy distributions of ^{238}U fission fragments as a function of the incoming neutron energy. The neutron emission is currently being analyzed in an attempt to determine the excitation energy dependence of nuclear dissipation. In parallel, we have developed the statistical model tools necessary to calculate the $^{238}\text{U}(n,f)$, $(n,2n)$, and $(n,3n)$ cross sections. We find that we need to invoke a "washing out" of the level density enhancement, which results from the axial deformation at the first barrier. The energy at which the "washing out" occurs determines the axial-deformation parameter γ , and it agrees with values determined by potential energy studies. In addition, the effect of preequilibrium neutrons using the geometry-dependent hybrid model needs to be incorporated. The excellent agreement with existing cross-section data gives us confidence in predictions we have made of the $^{237}\text{U}(n,f)$ cross section, which is of considerable importance to some applied programs. The predictions involve some adjustments of parameters to fit existing data obtained in a bomb shot and in critical assemblies.

Thermal Neutron Capture by ^{14}N

E. T. Jurney [(505) 667-4118] (P-DO), J. E. Lynn (P-17), J. W. Starnner (CST-15), S. Raman (Oak Ridge National Laboratory)

At the Omega West neutron-capture gamma-ray spectrometer, we have accurately measured the energies and intensities of gamma rays emitted in neutron capture by nitrogen (99.63% ^{14}N). A major reason was to establish this reaction as a standard for similar measurements on other nuclides. Above about 2 MeV, the resolution attained is better than that reported in all previous studies of the $^{14}\text{n}(n,\gamma)$ reaction. In setting our standard on the energy scale, we have concluded that our value for the neutron separation energy of ^{15}N disagrees with Wapstra's 1990 standard [(A. H. Wapstra, *Nuclear Instruments and Methods* **292**, 671 (1990)] by about 80 eV. We have placed the 60 gamma rays observed into the known level scheme of ^{15}N . Of particular interest are the primary gamma rays from the neutron-capture state. The very-low-capture cross section of ^{14}N (79 mb) suggests that these are likely to be explained by the direct-capture mechanism. Surprisingly, the capture cross section is much lower than the direct-theory estimate; this cross section has in fact been a long-standing puzzle because it was believed to be too high relative to expected resonance contributions! We have now resolved the problems by recognizing that there are three contributing (and interfering) elements in the transition amplitudes: (1) potential capture, (2) valence capture, and (3) compound-nucleus capture (from two bound levels). In some of the most important transitions, these components destructively interfere. Quantitative consistency has been established among all eight measured primary transitions, and the neutron-valence-capture mechanism has been established as an important process in a resonance level previously known only from proton excitation in the $^{14}\text{C}(p,\gamma)$ reaction.

P-17: Neutron and Nuclear Science

Neutron Nuclear Astrophysics

P. E. Koehler [(505)-667-7237] (P-17), H. A. O'Brien, Jr. (P-DO), F. Käppeler, H. Schatz (KfK, Karlsruhe, Germany), Yu. M. Gledenov, Yu. P. Popov, (Joint Institute for Nuclear Research, Dubna, Russia), R. W. Kavanagh (California Institute of Technology), M. Wiescher (University of Notre Dame), R. B. Vogelaar (Princeton University)

Measurements were made of several neutron-induced cross sections of interest to nuclear astrophysics. The experiments were undertaken at the Manuel Lujan, Jr., Neutron Scattering Center (LANSCE); at the Oak Ridge electron linear accelerator (ORELA) facility in Oak Ridge, Tennessee; and at the Karlsruhe Van de Graaff in Germany. First, the measurements revealed that the $^{17}\text{O}(n,\alpha)^{14}\text{C}$ and $^{14}\text{C}(n,\gamma)^{15}\text{C}$ reactions are crucial bottlenecks in the possible formation of heavy elements in nonstandard models of the big bang. Second, the $^{36}\text{Cl}(n,p)^{36}\text{S}$ cross section is a factor of 2.2 times smaller than the theoretical estimate used in previous nucleosynthesis calculations. The reduction in this rate should help alleviate the overproduction of ^{36}S seen in previous explosive nucleosynthesis calculations and may decrease the amount of ^{36}S made in calculations of the weak component of the s-process of nucleosynthesis (which would make the good agreement between the observed and calculated ^{36}S abundance from the s-process worse). Third, the $^{35}\text{Cl}(n,p)^{35}\text{S}$ reaction probably does not play an important role in the s-process. Fourth, the $^{14}\text{N}(n,p)^{14}\text{C}$ cross section is very close to a $1/v$ shape near thermal energy as assumed in the normalization of our previous measurements. These new data confirm the older, larger value for this reaction rate over a relatively recent recommendation of a threefold reduction in the rate. And finally, the $^{26}\text{Al}(n,p)^{26}\text{Mg}$ cross section is approximately a factor of 2 larger than previously thought, whereas our $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$ measurements are in good agreement with previous measurements made via the inverse reaction. The impact of these new data on the nucleosynthesis of the radioisotope ^{26}Al is currently being investigated. We have also successfully tested two new (n,charged particle) detectors, which should allow us to measure smaller cross sections or to use a wider variety of targets in the measurements. A compensated ionization chamber was used to measure the $^{17}\text{O}(n,\alpha)^{14}\text{C}$ cross section to approximately 2 MeV. In addition, zinc sulfide was used as both the target and the detector to measure the $^{33}\text{S}(n,\alpha)^{30}\text{Si}$ cross section.

Neutron-Proton Bremsstrahlung Studies at the Los Alamos Meson Physics Facility and the Weapons Neutron Research Facility

J. E. Koster [(505) 665-0250] (P-17, now in NIS-6), D. R. Mayo, R. O. Nelson, S. A. Wender (P-17), M. E. Schillaci (ESH-12), Collaborators from Lawrence Livermore National Laboratory, the University of California at Davis, Institut des Sciences Nucléaires at Grenoble (France), and the University of Saskatchewan (Canada)

Neutron-proton bremsstrahlung (NPB) should provide insight into nucleon-nucleon (NN) interaction, which is fundamental in understanding nuclei. This process is the lowest-energy inelastic reaction that can occur and is the only inelastic reaction possible below the pion-production threshold at 280 MeV. NPB probes different aspects of the NN interaction from proton-proton bremsstrahlung (PPB). In particular, NPB is sensitive to meson exchange currents. Also, electric dipole radiation is not inhibited in NPB. Thus, the NPB cross section is much greater than the PPB cross section. NPB reactions may therefore be the

predominant source of the high-energy gamma rays observed in heavy-ion reactions. Data on the NPB reaction have been very sparse primarily because of the difficulty in producing intense, high-energy neutron beams. The NPB reaction is studied with the high-intensity, high-energy spallation neutron source at the WNR Facility at LAMPF. We have constructed a liquid-hydrogen target and a multi-element gamma-ray detector. Measurements were completed and data analyzed on inclusive gamma-ray production at 90° and 117° for incident neutron energies from 100 to 500 MeV. Detector-element responses have been measured at a tagged-photon facility with the results under study to check our detector simulations. A publication of the results will provide a comparison of our data with previous data and calculations. A differential measurement has been initiated by measuring the outgoing nucleons from NPB in an array of nine plastic Phoswich detectors and six plastic scintillating neutron detectors. This experiment will be refined to provide the most extensive data yet for testing NPB calculations.

Accelerator Production of Tritium

P. W. Lisowski (P-17)

The Accelerator Production of Tritium (APT) project sponsored by DP-40 involves the preconceptual design of an accelerator system to produce tritium for the nations stockpile. Tritium is a radioactive isotope of hydrogen used in nuclear weapons. Because tritium has a half-life of 12.3 years it must be periodically replenished. The alternatives for producing tritium include construction of a nuclear reactor or use of an accelerator system. The accelerator system has important environmental, safety, and health (ES&H) advantages over a reactor, but it requires a substantial amount of electrical power. The concept under study by Los Alamos would use a high-intensity (200 mA), medium-energy (1,000 MeV) proton linear accelerator as the driver of a neutron source. The neutrons would subsequently be used in a heavy-water moderator region to interact with ^3He contained in aluminum tubing to produce tritium through the (n,p) reaction. The design of the neutron source and tritium-breeding blanket, as well as coordination of three experiments in support of APT, is operated out of P-17. At present, an initial design stage is complete. We are now working toward providing better design information for the DOE in support of the Complex-21 Record of Decision, which has been scheduled for January 1995.

Intermediate Structure in the Neutron-induced Fission Cross Section of ^{236}U

J. E. Lynn [(505) 667-1053], P. W. Lisowski (P-17), G. L. Morgan (P-15), W. E. Parker (Lawrence Livermore National Laboratory), A. D. Carlson (National Institute of Standards and Technology), N. W. Hill (Oak Ridge National Laboratory)

Previous measurements of the fission cross section of ^{236}U at low neutron energies disagree by large factors. Also, they show none of the intermediate resonance structure (as distinct from normal fine-structure resonances) that are characteristic of the fission cross sections of other actinide nuclides. We have re-measured this cross section at the LANSCE neutron source using ionization-chamber techniques for direct detection of the fission products, and we have found that it is very much lower than previously reported. In fact, very few of the resonances that are found in the ^{236}U total cross section have a detectable fission width, but those that do appear in the fission cross section fall into narrow clusters.

We have thus resolved a long-standing problem in the nuclear structure of the actinides—namely, the apparent absence of intermediate structure associated with the super-deformed phase of the ^{237}U compound nucleus. We have shown that an intermediate structure does exist for this nuclide, although at a much weaker fission-cross-section level than had previously been sought. Also, the characteristics of this structure are reasonably consistent with the systematic trends of the double-humped fission-barrier parameters as determined from a host of other experimental evidence on the actinide nuclei.

Neutron Capture by ^{43}Ca

J. E. Lynn [(505) 667-1053] (P-17), M. C. Moxon, J. A. Harvey, S. Raman (Oak Ridge National Laboratory), W. Ratynski (Soltan Institute, Poland)

The thermal neutron capture of ^{43}Ca is known to be strongly affected by resonances (unlike the even calcium isotopes), but knowledge of resonance properties has been very poor. At the ORELA Facility, we have now made accurate, high-resolution measurements of the total cross section on a sample enriched to 49% in ^{43}Ca . From these measurements, we have obtained precise values of the parameters of several of the lowest-energy resonances, including their spin assignments. From these parameters, we can make an accurate assessment of resonance effects at thermal neutron energy and, hence, a complete data analysis of the thermal-neutron-capture gamma-ray spectrum. An interesting situation is revealed in which compound-nucleus capture (from the resonance wings) and direct capture (which includes a valence component from the resonances) are of almost equal significance despite the fact that the valence process is expected to be of minor importance at the resonance energies. The spectrum of the compound-nucleus capture does not appear to be consistent with standard models of the capture process.

Gamma-ray Production Measurements

R. O. Nelson [(505) 667-7107] (P-17)

High-energy gamma-ray production from fast-neutron-induced reactions on actinide samples is of interest for programmatic reasons and for basic nuclear physics. In 1992, a new experiment was initiated to measure such cross sections. Preliminary data were acquired on ^{239}Pu , and more extensive data were obtained for ^{238}U . In 1993, the measurements were continued with both ^{238}U and ^{235}U samples. In addition to the sample-in data, considerable sample-out and other data must also be acquired to correct for the large gamma-ray and neutron-induced backgrounds. The neutron energy range covered is from a few MeV to over 20 MeV. The gamma-ray energy region of interest extends from 10 to 25 MeV. The dominant contribution to the gamma-ray spectrum in this energy region is expected to come from neutron-capture reactions. Such measurements are very difficult to make because of the small capture cross section and the large neutron and gamma-ray backgrounds typically encountered. BGO gamma-ray detectors are used because of their good gamma-ray efficiency relative to the neutron-detection efficiency. Reduction of the data is now in progress. Analysis of data previously acquired with BGO gamma-ray detectors on C, ^{14}N , and ^{15}N is nearing completion. Reduction of other data from a wide variety of targets obtained with high-resolution germanium detectors is also continuing.

Fundamental Symmetries with Neutrons

S. J. Seestrom [(505) 667-0156], C. M. Frankle, S. A. Wender, P. E. Koehler, C. D. Bowman (P-17), J. D. Bowman (spokesman), S. Penttila, Y. F. Yen (P-11), J. N. Knudson (AOT-7), V. W. Yuan (AT-10), N. R. Roberson (Duke University), C. R. Gould, D. G. Haase, G. E. Mitchell (North Carolina State), E. I. Sharapov, Yu. P. Popov (Joint Institute for Nuclear Research, Dubna, Russia), H. Postma (Delft, the Netherlands), P. P. J. Delheij (TRIUMF, Canada), A. Msaïke, Y. Masuda (KEK, Japan)

As part of the TRIPLE collaboration, we have developed a polarized neutron beam at LANSCE for study of fundamental symmetries. In 1993, we used a new neutron polarizer for the first time. This polarizer uses the dynamic-nuclear-polarization technique to polarize protons in ammonia in a 4-T magnetic field. With this system, we achieved proton polarizations of 80 to 90% and neutron polarizations of 60 to 65%. Two new detectors were developed: (1) a ^{10}B -loaded liquid scintillator detector for measuring neutron transmission and (2) a CsI(pure) gamma-ray detector for studying neutron capture. The ^{10}B detector was successfully used to take data on a number of samples (i.e., ^{238}U , ^{232}Th , indium, niobium, and silver) during the 1993 beam time at LAMPF. Multiple cases of parity violation (PV) were observed in a number of these samples. The experimental uncertainty obtained for asymmetries in ^{238}U was reduced by a factor of 20. The sign effect previously observed in ^{232}Th was reproduced with eight of eight significant effects of the same sign. All other samples showed both positive and negative effects. The gamma-ray detector was not available in time for the 1993 experimental period, but it will be ready for the first beam available in 1994. PV was measured in ^{113}Cd using BaF_2 to detect gamma rays from the neutron-capture reaction on a 100-g isotopically enriched sample supplied by the Joint Institute for Nuclear Research. Multiple cases of PV were observed in ^{113}Cd , including the highest-energy resonance (374 eV) in which PV was observed.

Dynamic Measurements

W. J. Trela [(505) 665-4123] (P-17), K. Meggers, H. G. Priesmeyer (Kiel University, Kiel, Germany)

Nucleation and growth problems, or time/temperature/transformation (TTT) processes, pervade much of materials research. However, the measurement of such processes remains largely unexplored. The determination of structure and the measurement of a given property are usually performed separately, often not *in situ* (e.g., the study of quenched specimens or the use of ambient structural data to interpret properties under extreme conditions), and usually with different specimens. Our development of the short-burst neutron transmission technique allows us to conduct investigations at many points in time during a phase transformation because spectra are recorded continuously *in situ* from a single sample. We have measured the decomposition of austenite (fcc structure) into bainite (bcc structure) within globulitic gray iron in real time. This measurement was done as a diffusion-controlled, eutectoid-solid-state phase transformation and was accomplished by recording continuously 30-s transmission spectra of thermal neutrons from the sample. Our results show that the transformation follows the Avrami law during the intermediate stages (between 250 s and 500 s). The transformation quickly reaches its completion for the Avrami law, but we see the progression of the transformation break off after approximately 500 s. The transformation

proceeds slowly for the next 2500 s to about 80% completion and then stops because the driving force for the transformation is not constant. Initially, the energy balance is dominated by the increase of free energy of the single atoms. During the initial growth of the new phase, the bainite grains grow very quickly and relatively undisturbed for the first 500 s. The bainite grains then start to impinge against each other, and the gain in free energy is compensated by the increasing energy of distortion. The latter occurs because the specific volume of the austenite is much smaller than that of the bainite. Thus the decomposition of the austenite becomes more retarded until it almost completely stops. We have shown that through this neutron transmission technique it is possible to follow a structural phase transformation *in situ* in real time and to produce a complete TTT diagram.

Accelerator Production of Tritium Spallation Radionuclide Production

J. L. Ullmann [(505) 667-2517], A. Gavron, J. D. King, P. W. Lisowski, D. R. Mayo, R. O. Nelson, L. S. Waters, S. A. Wender, C. Zoeller, D. Jagnow, R. Laird (P-17), J. E. Koster (NIS-6), G. Butler, M. Fowler, R. Gritz, J. Wilhelmy, M. A. Yates (CST-13), W. B. Wilson (T-2)

As part of the scientific studies associated with the APT project, we measured the stopping-target spallation-radionuclide yield for 800-MeV protons on tungsten and lead. The normal spallation problem involves a study of the isotope yield for a definite incident energy, but the stopping-target problem involves understanding both the secondary-particle spectrum and the isotope yield. The experiment was done at the WNR Target 2 Facility with the external proton beam at LAMPF. Thin foils of tungsten or lead were inserted into a stopping-length target of the same material to sample the secondary-particle environment. Radioisotopes were identified by their characteristic gamma rays. Preliminary analysis of a central foil on the beam axis showed that calculations matched yield measurements to within a factor of 2 for 56% of the radionuclides identified.

Neutron-Elastic-Scattering Studies at the Weapons Neutron Research Facility

J. L. Ullmann [(505) 667-2517] (P-17), D. S. Sorenson (P-15), J. H. Osborne, F. P. Brady, J. L. Romero (University of California, Davis), A. G. Ling (TRIUMF, Canada), B. K. Park (New Mexico State University)

A large solid-angle total-energy neutron detector was constructed by adding scintillating neutron-to-charged-particle convertors to the P-17 (n,p) detector. Preliminary studies of detector operation and neutron elastic scattering from about 50 to 250 MeV were made on the 90-m flight path at the WNR Target 4 Facility. Initial targets were ^{nat}Ca and ^{208}Pb . Analysis of forward-angle elastic scattering is under way. This experiment will provide the first systematic survey of neutron elastic scattering in the intermediate-energy range.

Studies of the (n,p) Reaction from 50 to 250 MeV

J. L. Ullmann [(505) 667-2517] (P-17), D. S. Sorenson (P-15), B. K. Park (New Mexico State University), J. Rapaport (Ohio University), F. P. Brady, J. L. Romero (University of California, Davis), A. G. Ling (TRIUMF, Canada)

Additional medium-energy (n,p) studies were made on the 90-m flight path at the WNR Target 4 Facility with a large solid-angle cesium iodine detector array. The $^{10}\text{B}(\text{n,p})\text{gs}$ reaction was studied to measure the energy dependence of the effective NN isovector tensor interaction. Although preliminary results have been submitted for publication, a more complete measurement of the reaction has been made and is under analysis. A second experiment, which was designed to measure the isovector spin- and nonspin dipole excitations in ^{51}V , has completed data collection, and analysis is beginning.

Appendix A

Physics Division Data, FY93

Physics Division Groups: Principal Missions, Budgets, and Sizes

High Energy-Density Physics (P-1)	Costs: \$7.6 million Staff Members: 18.7 FTE Graded Employees: 18.4 FTE
Medium-Energy Physics (P-2)	Costs: \$3.6 million Staff Members: 18.5 FTE Graded Employees: 5.1 FTE
Subatomic Research and Applications (P-3)	Costs: \$8.2 million Staff Members: 16.7 FTE Graded Employees: 11.9 FTE
Laser-Matter Interaction and Fusion Physics (P-4)	Costs: \$4.8 million Staff Members: 12.0 FTE Graded Employees: 10.4 FTE
Biophysics (P-6)	Costs: \$3.0 million Staff Members: 13.1 FTE Graded Employees: 4.1 FTE
Condensed-Matter and Thermal Physics (P-10)	Costs: \$4.1 million Staff Members: 15.3 FTE Graded Employees: 7.2 FTE
Fast-Transient Plasma Physics (P-14)	Costs: \$8.8 million Staff Members: 26.6 FTE Graded Employees: 17.5 FTE
Applied Physics Experiments and Imaging Measurements (P-15)	Costs: \$11.4 million Staff Members: 34.1 FTE Graded Employees: 22.4 FTE

Costs: \$3.2 million
Staff Members: 12.6 FTE
Graded Employees: 5.6 FTE

Costs: \$3.4 million
Staff Members: 8.3 FTE
Graded Employees: 2.8 FTE

Neutron and Nuclear Science (P-17)

Physics Division Office (P-DO)

Physics Division Costs, FY93.

***Other DOE**

Fusion Energy 23%
High-Energy Physics 1%
Nuclear Physics 46%
Basic Energy Sciences 18%
Biological and Environmental Research 6%
Other 6%

Appendix B

Publications, Invited Talks, Book Chapters, and Patents

Journal Articles

- O. Adriani *et al.*, "An S Matrix Analysis of the Z^0 Resonance," *Physics Letters B* **315**, 494 (1993).
- O. Adriani *et al.*, "Determination of Quark Electroweak Couplings from Direct Photon Production in Hadronic Z Decays," *Physics Letters B* **301**, 136 (1993).
- O. Adriani *et al.*, "Determination of the Effective Electroweak Mixing Angle from Z^0 Decays," *Physics Letters B* **309**, 451 (1993).
- O. Adriani *et al.*, "Inclusive Search for the Charmless Radiative Decay of the b-quark ($b \rightarrow s\gamma$)," *Physics Letters B* **317**, 637 (1993).
- O. Adriani *et al.*, "Measure of R_B from Hadronic Decays of the Z^0 ," *Physics Letters B* **307**, 237 (1993).
- O. Adriani *et al.*, "A Search for the Neutral Higgs Boson at LEP," *Physics Letters B* **303**, 391 (1993).
- O. Adriani *et al.*, "Search for a Z' at the Z^0 Resonance," *Physics Letters B* **306**, 187 (1993).
- O. Adriani *et al.*, "Search for Lepton Flavour Violation in Z^0 Decays," *Physics Letters B* **316**, 427 (1993).
- O. Adriani *et al.*, "Search for Narrow Vector Resonances in the X^0 Mass Range," *Physics Letters B* **313**, 326 (1993).
- O. Adriani *et al.*, "Search for Non-Minimal Higgs Bosons in Z^0 Decays," *Z. Physics C* **57**, 355 (1993).
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Invited Talks at National and International Conferences

- R. M. Baltrusaitis and C. A. Ekdahl, "Hydronuclear Experiment," 9th Biennial Nuclear Explosives Design Physics Conference, Lawrence Livermore National Laboratory, Livermore, California, November 8-12, 1993.
- R. M. Baltrusaitis, C. A. Ekdahl, R. G. Cooper, E. Peterson, and C. E. Warn, "High Bandwidth Beam Current Monitor," 1993 Particle Accelerator Conference, Accelerator Science and Technology, Washington, D.C., May 17-20, 1993.
- R. M. Baltrusaitis, C. A. Ekdahl, and J. Stokes, "High Bandwidth Reaction History Measurement," 9th Biennial Nuclear Explosives Design Physics Conference, Lawrence Livermore National Laboratory, Livermore, California, November 8-12, 1993.
- E. Barberis, J. G. Boissevain, N. Cartiglia, J. A. Ellison, P. Ferguson, J. K. Fleming, K. Holzscheiter, S. Jerger, D. Joyce, J. S. Kapustinsky, J. Leslie, C. Lietzke, J. A. J. Matthews, A. P. T. Palounek, D. Pitzl, E. Reed, W. A. Rowe, H. F.-W. Sadrozinski, D. Skinner, W. F. Sommer, W. E. Sondheim, S. J. Wimpenny, and H.-J. Ziock, "Temperature Effects in the Radiation Damage of Silicon Detectors," 6th European Symposium on Semiconductor Detectors, Milan, Italy, February 24-26, 1992.
- D. B. Barlow, C. M. Fortgang, J. D. Gilpatrick, R. E. Meyer, A. M. Rendon, D. S. Warren, and M. D. Wilke, "Prototype Flying-Wire Beam-Profile Monitor," 1993 Particle Accelerator Conference, Accelerator Science and Technology, Washington, D.C., May 17-20, 1993.
- M. Berenguer, H. Sorge, H. Stocker, and W. Greiner, "Meson-Meson Interactions and Phi-Enhancement in Nucleus Collisions," 9th Winter Workshop on Nuclear Dynamics, Key West, Florida, January 30, 1993.
- R. L. Blake, J. C. Davis, D. E. Graessle, T. H. Burbine, and E. M. Gullikson, "Optical Constants and Scattering Factors from Reflectivity Measurements: 50 eV to 10 keV," International Conference on Anomalous Scattering, Malente, Germany, August 17-21, 1992.
- R. Bowers *et al.*, "Variable Energy Solid Driver on Pegasus II for Weapons Applications," 9th Biennial Nuclear Explosives Design Physics Conference, Lawrence Livermore National Laboratory, Livermore, California, November 8-12, 1993.
- T. J. Bowles, "Where Have All the Neutrinos Gone? Status of Present Solar Neutrino Experiments," APS General Meeting, Washington, D.C., April 20-24, 1992.
- T. J. Bowles, "Recent Results from SAGE," 15th International Conference on Neutrino Physics and Astrophysics, Granada, Spain, June 7-12, 1992.
- T. J. Bowles, "Weak Interaction Physics," INSF Nuclear Physics Summer School, Corvallis, Oregon, July 6-17, 1992.
- T. J. Bowles, "Neutrino Mass," Texas/PASCOS Conference, Berkeley, California, December 13-18, 1992.

K. S. Bradley, J. C. Fernandez, P. Drake, J. DeGroot, and S. H. Batha, "Toward Understanding SBS in Laser-Produced Plasmas," APS Division of Plasma Physics 35th Annual Meeting, St. Louis, Missouri, November 1-5, 1993.

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K. Croasdell, "Recording Reaction History with Digital Systems," 9th Biennial Nuclear Explosives Design Physics Conference, Lawrence Livermore National Laboratory, Livermore, California, November 8-12, 1993.

C. G. Davis, "Computational Astrophysics: Pulsating Stars," 2nd International Conference on Computational Physics, Beijing, China, September 13-17, 1993.

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A. Hime, "Do Scattering Effects Resolve the 17-keV Conundrum?" APS Meeting of the Division of Particles and Fields, Batavia, Illinois, November 10-14, 1992.

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F. Kappeler, M. Wiescher, and P. E. Koehler, "Neutron Reactions: Astrophysical Quests and Laboratory Approaches," AUSTRON Workshop, Austria, May 3-4, 1993.

N. S. P. King, K. L. Albright, T. E. McDonald, G. J. Yates, and B. T. Turko, "High-Frame Rate CCD Cameras with Fast Optical Shutters for Mine Detection and Surveillance Applications," Imaging and Technology Conference and Exposition, Items '93, Washington, D.C., June 1993.

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- A. P. T. Palounek, "A Summary of the Workshop on Simulating Accelerator Radiation Environments," International Conference on Monte Carlo Simulation in High-Energy and Nuclear Physics, Tallahassee, Florida, February 22-26, 1993.
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- J. C. Peng, "Past, Present, and Future of Pi,Eta Experiments," Workshop of Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Facilities, Brookhaven National Laboratory, Upton, New York, March 4-6, 1993.
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- A. Picklesimer, "A Few Δ 's in a Few Few-Nucleon Systems," 1993 Few-Body Gordon Conference: Dynamics of Simple Systems in Chemistry and Physics, Andover, New Hampshire, August 16-20, 1993.
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