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E-DIVISION ACTIVITIES REPORT

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July 1983

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E-Division Activities Report

July 1983

ABSTRACT

This report describes some of the activities in E (Experimental Physics) Division during the past year. E-Division carries out research and development in areas related to the missions of the Laboratory. Many of the activities are in pure and applied atomic and nuclear physics and in materials science. In addition, this report describes development work on accelerators and on instrumentation for plasma diagnostics and for electron-accelerator diagnostics, nitrogen-exchange rates in tissue, and breakdown in gases by microwave pulses.

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INTRODUCTION

E (Experimental Physics) Division carries out basic and applied research in atomic and nuclear physics, in materials science, and in other areas related to the missions of the Laboratory. Some of the activities are cooperative efforts with other divisions of the Laboratory, and, in a few cases, with other laboratories. Many of the experiments are directly applicable to problems in weapons and energy, some have only potential applied uses, and others are in pure physics.

E-Division issues an annual report which describes some of the activities in the division during the preceding year. The preceding report (UCID-17271-82) was issued in July 1982. The report gives a brief review of the program of the Division. Not all the activities are included every year. The results of the research are published in detail in the scientific literature and are reported at scientific meetings. References to papers and conference proceedings published since the preceding report of this series are listed in the present report.

LLNL publishes monthly in the Energy and Technology Review (UCRL-52000) descriptions of programs of general interest. Articles describing E-Division activities are reprinted in the E-Division annual reports. The following reprints were included in the previous reports:

Probing Nuclei with LLL's Electron Linear Accelerator (1978)

RTNS: A Tool for Studying Neutron Damage (1978)

The Magnetic-Quadrupole Spectrometer: Studying Neutron Reactions (1978)
Pulsed Sphere Measurements for Weapons and Fusion Reactor Design (1978)
Measuring Hydrogen-Isotope Distribution Profiles (1978)
Nuclear Modeling at the LLL Cyclograaff (1979)
Studying Materials with Positrons (1980)
Probing Nuclear Structure with Electron Scattering Techniques (1980)
Channeling Radiation (1981)
ZAPP: A Facility for Studying Radiation from Hot, Dense Plasmas (1982)
Ozone, Respiration, and "The Bends" (1982)
Slow Positrons from the 100 MeV Linac (1982)
Ion-Atom Interactions (1982)

The present report includes:

ZAPP Upgraded

Joint U.S.-Japanese Neutron-Source Program

How Old is the Universe?

Neutron Diagnostics for Magnetically Confined Plasmas

ACCELERATORS

Many of the activities of the Division are centered around seven accelerators: A 100-MeV electron linear accelerator (Linac), three 400-kV dc high-current accelerators, a 3-MV electrostatic accelerator, a 6-MV tandem electrostatic accelerator, and a 76-cm cyclotron. The cyclotron can be used as an injector for the tandem accelerator (Cyclograaff). With these accelerators, beams of neutrons, photons, and charged particles can be produced, and the interaction of these projectiles with nuclei, atoms, and solids is studied.

The oldest of the three 400-kV accelerators ("ICT") produces 25 mA of atomic hydrogen ions, the newer ones ("RTNS II") are designed to produce 150 mA.

All the accelerators can serve as neutron sources. The Linac permits the simultaneous study of neutrons of energies from thermal to about 60 MeV by observation of the neutron time-of-flight over distances as long as 250 m. The 400-kV accelerators serve primarily as intense sources of 14-MeV neutrons and the tandem is used to produce mono-energetic neutrons whose energy may be varied between 1 and 26 MeV.

Most of the charged-particle interaction experiments are performed with the Cyclograaff. Reactions producing charged particles are studied with the aid of a high resolution broad-range magnetic spectrometer as well as with solid-state detection systems. Low-energy gamma rays produced in charged-particle interactions are detected and their energy is measured in Ge-Li detectors, higher-energy gamma rays in a NaI scintillator with an anticoincidence shield. This latter detector has an unusually large volume: 10 dm^3 for the NaI crystal and 1 m^3 for

the plastic scintillator that provides the anticoincidence signal. Neutrons produced in charged-particle reactions are detected and their energy is measured in a well-shielded time-of-flight facility that permits simultaneous observation at 16 angles.

The 3-MV electrostatic accelerator is used for studies of ion-atom collisions and ion interactions with solids.

Intense Source of 14-MeV Neutrons (RTNS-II)

The RTNS-II facility provides an intense source of 14-MeV neutrons used to study the effects of fusion neutrons on various materials. The facility is now jointly supported by the governments of Japan (Monbusho) and the U.S. (DOE).

Japanese equipment installed at RTNS-II during the year include an X-ray diffractometer and a 200 kV Transmission Electron Microscope (TEM). Both pieces of equipment are being used in the analysis of samples irradiated at RTNS-II.

The original plans for the RTNS-II facility called for two accelerators each operating at 400 kV and producing 150 mA of deuterons. Both budgetary and technical difficulties have limited operations to one accelerator operating at 360 kV and about 80 mA. With the availability of additional support from Japan the second accelerator was completed, and it produced neutrons for the first time on 16 June 1983.

The current had to be limited because of delays in the construction of the 50-cm diameter rotating targets. Although a few 50-cm targets have been used as they became available, the supply is not yet adequate. Loading of the targets with tritium is being shifted from Oak

Ridge to Livermore, and more targets are expected to become available soon so that operation at higher current and larger neutron source strength should be possible in the near future.

Between July 1982 and June 1983 a total of 7×10^{19} neutrons was produced with 5×10^6 C of beam for irradiations performed for 42 experimenters 24 of whom were from Japan. The experiments included the following investigations:

Metals and alloys: Microstructure with TEM; positron annihilation studies; void and bubble formation; electrical resistivity studies; mechanical properties; activation analysis; X-ray diffraction.

Insulators: Electrical/mechanical properties.

Polymer materials: Mechanical strength.

Superconductors: Critical temperature, field and current; fluxoid pinning strength.

Optical components: Surface treatment of glasses using fission fragments to reduce reflectivity; optical transmission.

Adhesives and sealants: Changes in properties.

Electronic components and circuits.

Radioactive Beam Development

Secondary beams of the radioactive nuclides have been produced by bombarding hydrogenous targets with accelerated stable nuclides. ^7Be is obtained through the $^1\text{H}(^7\text{Li}, ^7\text{Be})$ reaction, and ^{13}N through the reaction $^2\text{H}(^{12}\text{C}, ^{13}\text{N})$. Radioactive projectiles are of interest for studies of astrophysical processes, in advanced fuel cycles for fusion reactors, and in weapons development. Another application of such projectiles is in ion implantation.

The radioactive beam has been used to implant ^7Be in a silicon detector for a measurement of the ^7Be decay gamma rays, and for a determination of the ^7Be decay branching ratio to the first excited state of ^7Li .

Accelerator Operations

The tandem electrostatic accelerator, the cyclotron, the oldest 400-kV high current accelerator (ICT) and the Linac share the same operating crew so that there are limitations on their simultaneous operation. During the past year the tandem accelerator was operated by itself for about 1400 hours and in combination with the cyclotron for 600 hours. Beams produced were protons 40% of the time, deuterons 40%, alpha particles or Li ions 10%, and heavier ions about 10% of the time. The ICT accelerator operated for 250 hours. The Linac served as a neutron source for 1000 hours, as a gamma-ray source for 200 hours, and as a positron or electron source for 800 hours.

Accelerator Development

The tandem accelerator can serve as a source of pulsed neutrons of sub-nanosecond width for use in neutron scattering experiments. The neutrons are produced with (p,n) or (d,n) reactions. With pulsed beams of protons or deuterons, pulsed neutrons with energies from less than 1 MeV to 26 MeV may be obtained. Improvements in the light-ion pulsing system during the past year have quadrupled the short-pulse peak currents available for neutron scattering experiments. Deuteron beams with a period of 500 ns and widths of 0.9 to 1.5 ns and average currents of 1.2 to 2.5 μA have been obtained. Work currently in progress on the bunching system is expected to shorten the pulses and increase the current further.

NUCLEAR PHYSICS

Fission

The angular distribution of fission fragments produced in the fission of ^{232}Th is being measured with a small enough neutron energy spread to resolve the fine structure observed in the fission cross section near the fission barrier. Analysis of the angular distribution and cross section data in terms of the statistical model yields information about the nuclear potential energy surface as a function of nuclear deformation (the double-humped barrier). The present data have adequate statistics for energy intervals of 20 keV for neutron energies from 1 to 11 MeV. The results of the fission fragment measurements are consistent with the less complete data in the literature. Additional data should increase the statistical accuracy so that a neutron energy interval of 4 keV may be used for the comparison of the data with model calculations.

Previously measured fission cross sections for actinide nuclei are being compared with Hauser-Feshbach calculations. A recently developed computer code has been used to calculate detailed fits to the measured ^{235}U and ^{245}Cm fission cross sections. The calculations do not reproduce the structure in the cross sections observed near 1 MeV. The two most important decay modes of the ^{236}U compound nucleus in this energy region are inelastic scattering and fission. For the calculation of inelastic scattering about 100 discrete levels in ^{235}U were included. The calculation of the fission decay used the generally accepted parameters for the ^{236}U fission barrier. The calculations suggest that the observed structure in the measured cross section may

be due to structure in the nuclear level density at excitation energies of one to two MeV. Such structure is not contained in the constant-temperature model generally used to represent the density in this excitation range.

Neutron Cross Section Measurements

A comprehensive study is underway to improve the reliability of predictions of neutron cross sections obtained from optical model calculations. These predictions are needed for many nuclei that cannot be studied experimentally. The study includes both experiments and model calculations--the latter are described in detail elsewhere in this report. Total neutron cross sections measured at the Linac from 3 to 60 MeV provide a stringent test of the energy dependence of the nuclear optical model, particularly for the so-called microscopic model, based on an effective nucleon-nucleon interaction, in which there are no adjustable parameters to describe the variation with energy. Precise total cross sections of ^{139}La , ^{140}Ce , ^{142}Pr and ^{142}Ce have been measured. A study of the Ca isotopes is in progress. Comparison of the data with microscopic model calculations showed that fitting the difference between the ^{140}Ce and ^{142}Ce cross sections as a function of energy was very sensitive to small changes in the depth of the imaginary part of the potential. The measured difference cross section has a substantial non-monotonic variation with energy which is reasonably reproduced by the microscopic model (without any energy-dependent parameterization) provided one increases slightly the depth of the ^{142}Ce imaginary potential over the value given by the microscopic model.

Neutron elastic scattering differential cross sections were measured with the fast neutron time-of-flight spectrometer at the Cyclograaff. Neutrons of 14.6 MeV energy were produced by the $D(d,n)$ reaction. Measurements have been completed for ^9Be , ^{12}C , ^{27}Al , ^{56}Fe , ^{59}Co , ^{89}Y , ^{93}Nb , ^{115}In , ^{140}Ce , ^{181}Ta , ^{197}Au , ^{208}Pb , ^{209}Bi , ^{232}Th , ^{238}U and ^{239}Pu .

A knowledge of the cross sections for neutron-induced reactions that result in the emission of light charged particles is important in assessing materials for fusion reactors, in the calculation of dose in biological materials, and in the understanding of nuclear reactions. Of particular interest now is the measurement of kerma factors which are directly related to the energy deposited locally in a material by neutrons.

Measurements of the alpha-particle emission from carbon bombarded by 14.1 MeV neutrons have been evaluated. Although the cross section for the $^{12}\text{C}(n,\alpha)^9\text{Be}(\text{g.s.})$ reaction agrees well with accepted values, the cross section for the $^{12}\text{C}(n,n'3\alpha)$ reaction was found to be much smaller than all previous determinations. This change results in a 25% smaller kerma factor of carbon for 14.1-MeV neutrons than the accepted value.

Because of the importance of the kerma factor of carbon for biomedical applications an independent direct measurement of this quantity was carried out. In a carbon-walled small proportional counter the energy distribution of charged particles emitted from the wall was observed. This distribution yields directly the kerma. This direct determination of the kerma factor agreed very well with that deduced from microscopic cross sections, i.e., was also much lower than

the accepted values. There is evidence that the kerma factor of carbon is a rapidly varying function of neutron energy between 14 and 15 MeV.

To be able to investigate the energy dependence of the kerma factor, a quadrupole-multiplet-transport system has been constructed for analyzing protons, deuterons, and alpha particles from reactions induced by neutrons with energies from a few MeV to 34 MeV produced at the Cyclograaff. In addition, a high voltage wire assists in the transport of the particles of low energy. This apparatus allows the continuation of the study of these reactions beyond the 14-15 MeV range where most previous investigations have been made.

Integral Experiments

The transport of neutrons in ${}^6\text{LiD}$ and the disintegration cross sections of ${}^6\text{Li}$ and ${}^7\text{Li}$ are studied by surrounding a 14-MeV neutron source (ICT) with a large ${}^6\text{LiD}$ cylinder. Samples of ${}^6\text{Li}$, ${}^7\text{Li}$ and activation foils are placed at many locations in the cylinder. Production of ${}^3\text{H}$ and ${}^4\text{He}$ in the Li isotopes is measured. The activation foils serve to determine the neutron flux distribution in the cylinder. The measurements are compared with Monte Carlo calculations to check the transport code and the evaluated neutron data file. The experiments also yield values of the (n,α) and (n,t) cross section of ${}^6\text{Li}$ and ${}^7\text{Li}$ for 14-MeV neutrons.

The spectra of secondary neutrons emitted when a large sample of ${}^{239}\text{Pu}$ was bombarded with 14-MeV neutrons were measured. The measurements were compared with Monte Carlo calculations to check the evaluated neutron data file.

A 5.1 cm diameter x 1.9 cm thick ^6Li glass scintillator has been used in a number of experiments to measure the low energy neutron leakage spectra from spherical assemblies bombarded at their centers with 14 MeV neutrons. The detector efficiency measured at both the tandem and Linac was 30% lower than that calculated employing Monte Carlo techniques and the ENDL cross section library. The 30% discrepancy is now understood and is due to the fact that the scintillator was actually 30% less efficient due to aging, had 30% less ^6Li content than stated by the manufacturer or a combination of the two effects. A new ^6Li glass detector was 30% more efficient than the old scintillator. The ^6Li content of the new scintillator was determined independently and agreed with the value used in the calculations.

Alpha Particle Reaction Cross Sections

By studying the energy dependence of nuclear reactions and the energy spectra of the reaction products, one can infer properties of the nucleus. Nuclear sizes and details of the optical model potential well can be probed by measurements of the total reaction cross sections. Properties of nuclei in excited states can be inferred from the energy spectra of the emitted particles.

Nuclides near mass 50 are studied by a coordinated series of experiments that include precise determinations of total alpha particle reaction cross sections by measuring (α, n) cross sections. These results allowed a choice between two conflicting sets of alpha-nucleus optical model parameters. The data on the particle-emission spectra from (α, n) , (p, n) , (n, p) , (n, n) , (p, p') , and (n, α) reactions provide information about densities of nuclear levels at excitation energies of

3-10 MeV. These studies require interactive analysis with a nuclear reaction code that models these compound nuclear reactions. This code, together with parameters derived from experiment, makes possible the calculation of nuclear reaction cross sections and particle-emission spectra over a wide range of targets, projectiles, and energies.

Expanded Capabilities and Applications of Precompound Decay Models

Precompound decay models, when coupled with equilibrium models, provide a powerful tool for predicting a very broad range of nuclear reaction data. Recently the 'hybrid' precompound decay formulation has been modified to consider multiple precompound decay which becomes important at energies beyond 50 MeV. Global parameter sets have been determined for use with this model as implemented in the precompound/evaporation/fission code ALICE/LIVERMORE 82. These values have been tested against spectra and yields for nucleon induced reactions between 14 and 164 MeV. The agreement is generally good, and the predictions of these calculations appear to be quite reliable.

Comparisons have been made of (α, xn) excitation functions in the actinide region, where treatment of precompound decay is essential to the understanding of fission decay versus evaporation probabilities. The global parameter set yielded excellent agreement without modification. The calculations have also been applied to reactions induced by stopped negative pions, where the quasi-deuteron capture mechanism may be tested. Agreement with a broad range of experimental neutron and proton spectra, and product yields supports the quasi-deuteron hypothesis, and also shows the broad range of nuclear reactions which may be treated by the precompound plus evaporation models.

Neutron Cross Sections Deduced from Proton Experiments

Attempts to deduce neutron scattering cross sections from proton scattering and charge-exchange cross sections have been continued by analyzing a complete set of data for the tin isotopes. The macroscopic Lane model was used to describe the (p,p) and (p,n) reactions, and the resulting coupled equations were solved using a search routine which varied the isoscalar and isovector strengths of the optical potential to achieve a good fit to both (p,p) and (p,n) differential cross sections simultaneously. The neutron potential was then calculated from these strengths and the resulting elastic scattering compared with Ohio University data at 11 and 24.5 MeV. Good agreement was achieved.

Using the coupled Lane equations in this "isospin consistent" manner is equivalent to making a full Coulomb correction for both the real and imaginary parts of the neutron optical potential. This means that the neutron potential is to be evaluated at an energy equal to the proton energy for the coupled equations minus the full Coulomb energy difference. In the absence of strong coupling effects these calculations using the coupled equations will be equivalent to Distorted Wave Approximation (DWA) calculations only if the latter use full Coulomb corrections. This has not been the case for the imaginary part of the potential in many DWA analyses in the literature and so these analyses, which have often led to conflicting conclusions regarding the deduction of neutron cross sections, may not be compared to the present work. Understanding the origins of the imaginary Coulomb correction requires a microscopic calculation. Some initial calculations (however, not yet applied to the charge-exchange reaction) are described in the next section.

Microscopic Modeling

During the past two years the capability to calculate neutron and proton scattering cross sections from a microscopic point of view has been developed. This work, done in collaboration with Florida State University was described in the 1982 E-Division progress report. In these calculations the input consists only of the neutron and proton densities of the target nucleus, and an effective interaction that describes the scattering of the projectile from the individual nucleons in the target. An important practical reason for undertaking such calculations is to furnish a description of elastic scattering (the "optical model") that is free of the large number of adjustable parameters in the conventional phenomenological models. In the conventional models there are so many free parameters that it is difficult to extrapolate the models very far to mass or energy regions where data have not been measured. A further important advantage of the microscopic model over the phenomenological treatment is that the physical input is well-defined. As an example, the model allows insight into how the Coulomb potential should be treated for proton scattering. This problem must be properly understood in order to infer neutron-scattering cross sections reliably from proton scattering measurements (see preceding section). The microscopic techniques are also very useful because they unify scattering experiments over a very wide energy range (about 7 MeV to 1 GeV). The development of effective interactions that are valid over this range is currently a topic of extensive study. These interactions are derived from free nucleon-nucleon scattering, and take into account the effects of the

nuclear medium on the scattering of two nucleons inside a nucleus. The resulting effective interactions depend on the energy of the scattering nucleons, and on the density of the nuclear medium. Also, the interaction is complex, which allows prediction of both real and imaginary parts of the scattering potentials.

During the last year there has been a systematic evaluation of neutron and proton elastic scattering over a wide mass and energy range ($A = 6$ to 209 and $E = 7$ to 200 MeV). The main purposes of the study were to evaluate the accuracy of several effective interactions; to understand how low in energy the model is useful; and to understand whether special problems arise in the treatment of light nuclei ($A < 40$). Even though the main body of work addresses neutron and proton scattering in the energy range 7 - 26 MeV which is most likely to be useful for applications, the intermediate-energy region (80 to 200 MeV) is important because it provides a particularly stringent test of the effective interactions. The following sets of data were used in the tests: a survey of 14.6 MeV neutron angular distributions in the mass range $9 \leq A \leq 209$, measured at the Cyclograaff; proton- and neutron-scattering data in the range 8 - 26 MeV on ^{54}Fe and ^{56}Fe , together with a similar study on ^{208}Pb ; neutron total cross sections on ^{140}Ce and ^{142}Ce measured at the Linac, along with a precise measurement of their ratio; and a survey of proton scattering differential cross sections and analyzing powers in the range 80 - 200 MeV on nuclides from ^{12}C to ^{208}Pb . In nearly all cases the model was compared with experimental data by least-squares fitting two normalizing parameters for the calculated real and imaginary parts of the optical potential to the measurements.

Several conclusions concerning the effective interactions have emerged from this comparison of the calculations with scattering data. Below 50 MeV, all versions of the model yield reasonable agreement with the data. One version, that of Jeukenne, Lejeune, and Mahaux (JLM), agrees particularly well with the data, with normalizing parameters very close to unity ($\pm 10\%$ for the real potential and $\pm 20\%$ for the imaginary). In fact, the agreement with data is nearly as good as for phenomenological potentials. However, the JLM model is not applicable at higher energies, nor is it readily extended to inelastic scattering. An older effective interaction, based on the Hamada-Johnson nucleon-nucleon potential, is somewhat less successful in reproducing the details of the angular distribution data in the range 7-50 MeV, but is particularly useful for studying Coulomb effects on proton scattering. Comparisons of neutron and proton scattering on ^{54}Fe , ^{56}Fe , and ^{208}Pb with this interaction show that reasonable agreement with the data is obtained with the same normalizing parameters for both neutron and proton scattering for the same incident energy. Therefore these comparisons demonstrate that neutron scattering predictions can be based on proton scattering measurements although this conclusion needs to be tested over a wider range of nuclei. A further conclusion about the nature of the effective interaction is that the optical-model spin-orbit potential in the range below 50 MeV can be explained almost entirely by the folding of the nuclear density with a very simple two-nucleon spin-orbit interaction that is independent of density and energy. This follows from a comparison of the model with experiments on ^{56}Fe and ^{208}Pb using polarized proton and neutrons. Comparison of the models with 14-MeV neutron scattering data on light nuclei shows

surprisingly good agreement, although there is a systematic trend for the microscopic calculations to yield increasingly too small back-angle ($>90^\circ$) cross sections as the mass decreases. The experiment and analysis of proton scattering on ^6Li discussed below raises the possibility that this deficiency is due to an exchange effect that is not included in the model.

Recently the microscopic model has been extended to inelastic scattering. Such calculations require the optical potential in the initial and final states, with a form factor (transition potential) that describes the inelastic transition. The transition potential is calculated in the same way as the optical potential; the effective interaction is the same, and the transition density (which may be partly determined by electron scattering experiments) replaces the particle density used in elastic scattering. Inelastic neutron and proton scattering on ^{54}Fe and ^{56}Fe to the first-excited (2^+) state has been chosen as a test case. Inelastic neutron cross sections in the 11-26 MeV range were measured in collaboration with Ohio University. Because the normalization of the effective interaction is determined by elastic scattering, the inelastic-scattering calculations are free of parameters. The proton transition density is fixed by electron scattering measurements, and the neutron transition density is the important unknown quantity. Comparison of neutron and proton scattering on the same nucleus allows the neutron density to be determined, since the unlike-nucleon interaction is much stronger than that for like nucleons. Calculations using both microscopic optical and transition potentials yield neutron and proton inelastic angular distributions in good agreement with the data over most of the measured

angular range. The ratios of neutron to proton transition density determined by these parameter-free calculations are close to 0.8 and 1.1 for ^{54}Fe and ^{56}Fe , respectively. These results are very close to the expectations of a model for excitation of quadrupole (2^+) transitions that predicts a suppression of the neutron transition density in ^{54}Fe owing to its closed neutron shell.

Measurements with Polarized Protons

The measurement of analyzing powers for proton scattering from ^6Li at energies of 25, 35 and 45 MeV at the Berkeley cyclotron has been completed. Angular distributions of the analyzing power for elastic scattering from about 30° to 140° have been measured at all three energies. Similar data were obtained for the analyzing power for inelastic scattering to the 3^+ , $T = 0$ state in ^6Li . The elastic analyzing powers have a maximum of about 0.8 at angles around 90° , and at 130° they have a minimum which becomes more negative as the bombarding energy increases. The inelastic analyzing powers exhibit a minimum of about -0.3 around 90° and a broad maximum at back angles.

These data were compared with calculations using several different models. For elastic scattering, a phenomenological optical model from the literature was used which was derived from previously published cross section data and a crude measurement of the analyzing power at 40 MeV. This calculation failed to reproduce the back angle minimum in the elastic analyzing power, even after reasonable parameter adjustment. Two microscopic optical model calculations, based on a density-dependent effective two-body interaction, were also tried--they, too, were unable to reproduce the back angle analyzing power data. (One

calculation predicted $+1.0$ at 120° , whereas the measurement was -0.4 .) Adjusting the strength of either the central or spin-orbit parts of the microscopic optical model potentials did not improve the fit. Similar difficulties were encountered with the inelastic analyzing power, where a distorted-wave calculation using a density-dependent effective force was out of phase with the data by 30° at 25 MeV, and by about 60° at 45 MeV.

An attempt was made to understand the disagreement between calculations and measurements of the analyzing power. Both the elastic and inelastic cross sections were reasonably well reproduced by the calculation. Coupled-channels effects, a spin-spin component in the optical potential, and a non-spherical shape for the ${}^6\text{Li}$ ground state were found not to be possible sources of the difficulty. The most likely explanation is an exchange effect, called heavy-particle pickup, which arises when antisymmetrization has been completely accounted for. The effective forces used in the calculations treat exchange approximately and only deal with the so-called knock-out exchange process, ignoring heavy-particle pickup and several other details. For intermediate and heavy nuclei, only the knockout exchange process is expected to be important; however resonating-group calculations indicate that the heavy-particle pickup process will have a significant effect in light nuclei, especially at back angles. This process results in an odd-even ℓ -dependence of the calculated resonating-group phase shifts which may be approximated by an ℓ -dependent local optical potential. The inferred ℓ -dependence taken from a resonating group calculation for nucleons on ${}^6\text{Li}$ at 35 MeV was used to modify the phenomenological optical model potential. With no adjustment of

parameters the calculated elastic analyzing power produced a minimum at back angles similar to the data. In a collaboration with theorists from Florida State University, both the microscopic optical model and distorted wave codes are being modified to include the ignored exchange effects so that a reasonable comparison between theory and experiment can be made. Analyzing powers of light nuclei appear to be particularly sensitive to this effect.

As a further application of the microscopic reaction model for inelastic scattering, differential cross section and analyzing powers have been measured for polarized-proton scattering on ^{14}C at the LBL 88" cyclotron. Data have been taken at 25 and 35 MeV. ^{14}C is interesting because inelastic electron scattering data are available to help determine the proton transition densities, and there are shell-model wave functions (Cohen-Kurath and Millener-Kurath) that predict the neutron transition densities. These predictions can be tested by the microscopic analysis of the proton-scattering experiment. The first-excited (1^-) state of ^{14}C is important because it is the mirror of the ^{14}O first-excited state that appears as a resonance in the $^{13}\text{N}(p,\gamma)$ reaction at low energies. This reaction is important in the "hot CNO" cycle in nuclear astrophysics. Since ^{13}N is unstable, its rate must be estimated from the proton and radiative widths of the resonance. Improved knowledge of the transition densities in the ^{14}C mirror state will lead to more reliable estimates of the radiative width of the ^{14}O resonance.

When a proton interacts with another proton or a neutron inside a nucleus, the forces governing that interaction are not necessarily the same as if the struck nucleon were not bound in a nuclear medium.

These medium corrections to the free nucleon-nucleon interaction can be expressed as a density dependence of the nuclear force, where the nuclear density in the interaction region is taken to be that of infinite nuclear matter. In collaboration with physicists from MIT and elsewhere this behavior has been established in the oxygen isotopes by a comparison of electron-scattering cross sections with proton scattering cross sections and analyzing powers. The electron measurements were performed at the Bates Laboratory and yield the charge distribution and charge densities. The proton measurements are sensitive to both proton and neutron distributions and transition densities. Earlier measurements were carried out with 135-MeV protons at the Indiana cyclotron. They have now been extended at Indiana to 180 MeV and to 318 and 500 MeV at the Los Alamos Meson Physics Facility, to map out the variation with energy of this density dependence of the nuclear force. At 500 MeV spin-depolarization parameters were also determined and should provide information about the details of the nucleon-nucleon force in the interior of nuclei.

Photonuclear Reactions

Progress has been made in identifying the energies and spins of highly excited levels in ^{17}O observed via photoneutron emission to the ground state of ^{16}O . The angular distributions measured at seven angles have been fitted with a Legendre polynomial. The statistical accuracy of the measurement limits extraction of coefficients to the first three in the energy range from 10 to 24 MeV. As a test of the reliability of the measured angular distributions, data from a ^{16}O target were also analyzed. The resultant coefficients agreed well with published results.

The spins of the strong resonances in the region from 10 to 16 MeV can be determined from the Legendre expansion coefficients. For the resonances in this region the coefficients of the P_1 term are consistent with zero. The spins of a number of resolved resonances have been determined by comparing the measured coefficient of the P_2 term with calculations for levels of spin $3/2$, $5/2$, and $7/2$. A shell model study employing various residual interactions is underway to try to predict the locations of these resonances.

In the nuclear shell model, six protons or neutrons mark the closing of the $p_{3/2}$ shell, and eight the $p_{1/2}$ shell. Both ^{12}C and ^{16}O exhibit characteristics of closed shells, while ^{18}O , with ten neutrons, shows clearly that the two valence neutrons outside the p shell not only exhibit open-shell characteristics, but strongly polarize the ^{16}O core. Therefore a study of the ^{14}C nucleus may show whether the two neutrons added to the ^{12}C core make this nucleus more like a closed-shell nucleus (like ^{16}O) or like an open-shell nucleus (like ^{18}O). These characteristics can be studied by observing the properties of the giant dipole resonance in photonuclear reactions. A study performed in collaboration with physicists from Canada and Australia indicates that ^{14}C behaves much more like ^{12}C and ^{16}O than like ^{18}O .

Electromagnetic Dissociation of Relativistic Heavy Ions

When a projectile nucleus moving with a velocity nearly equal to the speed of light passes near to (but does not actually collide with) a high- Z target nucleus, it can absorb a virtual photon from the electromagnetic field of the target nucleus and subsequently dis-

tegrate in flight, much as if it had absorbed a real photon in a photonuclear reaction. In a prior collaboration with LBL the reaction products (singles) from the electromagnetic dissociation of ^{18}O projectile nuclei were measured at the Bevalac. This year in a collaboration with LBL on ^{16}O , two (or more) reaction products were observed in time coincidence--a more demanding experiment. Such measurements yield much more detailed information on the reaction mechanism. These new data are being analyzed currently.

Electromagnetic Properties of the $2g_{9/2}$ Neutron Orbital

Presently information about the electromagnetic properties of the neutron $2g_{9/2}$ orbital is deduced from measured properties of ^{210}Bi . The information is intertwined with properties of the $h_{9/2}$ proton: moments of the neutron orbital are therefore subject to uncertainties in both the measured properties of the $h_{9/2}$ proton and the need to untangle one from the other.

The first few states in ^{210}Pb are described in the shell model as 2 valence neutrons in the $2g_{9/2}$ orbital (together with an inert ^{208}Pb core). Thus information about the $2g_{9/2}$ neutron orbital can be deduced from electromagnetic properties of these levels. Levels in ^{210}Pb were populated with the $^{208}\text{Pb}(t,p)^{210}\text{Pb}$ reaction at a bombarding energy of 16 MeV at the Los Alamos National Laboratory Van de Graaff. The lifetimes and magnetic moments of the $J^\pi = 8^+$ and 6^+ members of the $(2g_{9/2})^2$ multiplet were measured with the perturbed angular correlation technique.

The measurements yielded for the magnetic moment of the $2g_{9/2}$ orbital $\mu = -1.42(7) \mu_N$, and for the effective charge $q_{\text{eff}} = 0.88(5)e$. These results agree with the known systematics in the mass 208 region.

Structure of ^{90}Zr and ^{88}Zr

New spectroscopic information has been obtained for ^{90}Zr and ^{88}Zr . A level scheme has been obtained up to ~ 11 MeV excitation energy in these nuclei, at least for the first state of a given J^π . The new information was deduced from data obtained in a series of experiments using ^{18}O beams and $^{72,74}\text{Ge}$ targets at the BNL Tandem Van de Graaff.

For each nucleus, some 20 new levels were located; for each level, spin-parity, lifetime information, and details of its electromagnetic decay branching and multipolarity have been obtained. A shell model calculation is in progress to ascertain whether or not a model-space and interaction which gives reasonable predictions for the low-lying states can be extended to include these new high-spin, high-excitation levels.

The Gamow-Teller Strength Function for ^{90}Zr

Gamow-Teller (GT) transitions are beta-decay (charge exchange) processes which occur with a simultaneous spin-flip of the nucleon. They have been studied for many years by looking directly at beta-decay reactions. This procedure has the obvious drawback that only a limited range of excitation energy (corresponding to the beta decay endpoint) may be studied.

Recently (p,n) reactions have been studied for many nuclei at energies of about 100 MeV. These allow a determination of the Gamow-Teller strength function over a range of about 50 MeV. The conclusion reached by the investigators in these experiments is that the strength observed is less than would be required by the sum rule. Models involving a shift of considerable strength to the region of excitation corresponding to the delta resonance are being examined.

Specific predictions for the energy dependence of the GT strength function at low excitation may be obtained from shell model calculations. These results are useful because of their sensitivity to "configuration mixing", the degree to which various arrangements of nucleons are mixed into supposedly simple states. To the extent that such processes spread the GT strength out in a smooth fashion, they may provide an explanation (either partial or complete) for the missing GT strength.

An initial shell model study of this type has been carried out for ^{90}Zr . A simple model for this nucleus has the last ten neutrons filling the $1g_{7/2}$ orbit. More complicated calculations would allow one or two excitations of neutrons from this orbit (called one-particle one-hole and two-particle two-hole excitations, respectively). The ground state of ^{90}Zr was constructed for each of these restricted excitation schemes and the resultant GT strength function constructed. The added complexity of the two-particle two-hole calculation appears to be needed to understand the width of the experimentally observed peaks, but does not place significant strength in an unobservable flat "background". This result provides support for the delta resonance hypothesis and may have an important effect on r-process nucleo-

synthesis calculations as well, since the detailed shapes of GT strength functions for neutron-rich nuclei needed for r-process calculations can be obtained only from calculations.

The Branching Ratio in the Decay of ^7Be

The branching ratio in the electron capture decay of ^7Be to the ground and first excited states of ^7Li is an important quantity in nuclear physics. The gamma rays from the ^7Li first excited state are often utilized to normalize reactions which produce ^7Be . When a recent measurement at another laboratory of this branching ratio suggested a value of 15.4%, which is substantially above the previously adopted value of 10.4%, it seemed worthwhile to check this branching ratio. At the same time this was an excellent opportunity to test the performance of the recently completed radioactive ion beam spectrometer.

A 20-MeV ^7Be beam was directed into a $\Delta E - E$ surface-barrier detector telescope. Up to 10^8 ^7Be ions were implanted into three different stopping detectors. The gamma rays from the first excited state of ^7Li were counted with two different Ge(Li) detectors which were calibrated to an absolute precision of better than 2%. A final branching ratio of $10.7 \pm 0.2\%$ was obtained in agreement with the previously accepted value.

NUCLEAR ASTROPHYSICS

Neutron Capture Nucleosynthesis of Nd Isotopes

The abundances of neodymium isotopes are important as constraints in neutron-capture nucleosynthesis and also in the origin of meteoritic isotopic anomalies. Since the isotope ^{142}Nd occurs only in the s-process, it is particularly important to define the s-process abundance curve. Pure r-process Nd may have been identified in at least one inclusion in the Allende meteorite and a pure s-process component may also have been observed in the acid insoluble residues. To clarify these phenomena, however, better neutron capture cross sections for Nd are required for neutrons of energy between 5 and 200 keV. Such measurements have been made for ^{142}Nd , ^{143}Nd , ^{144}Nd , with the pulsed Van de Graaff facility at Karlsruhe, W. Germany. Preliminary 30 keV Maxwellian averaged cross sections of 62.5(5.3), 298(29), and 154(7) mb have been determined for ^{142}Nd , ^{143}Nd , and ^{144}Nd , respectively. These cross sections imply an s-process abundance for ^{142}Nd which is higher by several standard deviations than the best theoretical s-process curve. The implication is that perhaps some interesting astrophysics is contributing additional ^{142}Nd . This may be the result of recycling from thermally enhanced alpha decay of ^{144}Nd which would require the s-process to occur, however, at carbon-burning temperatures. When this peculiar behavior of ^{142}Nd is taken into account, it seems that the meteoritic isotopic anomalies can indeed be attributed to pure s- or r-process components.

Calculations of H-R Diagrams

Intermediate-mass stars (between 2 and 10 solar masses) are important in nucleosynthesis as progenitors of planetary nebulae (and therefore contributors of C and N isotopes to the interstellar medium) and also as possible candidates for a carbon deflagration supernova. A comparison of astronomical data with calculated H-R diagrams constructed from evolutionary models of stars in this mass range can test the input physics in the models and at the same time determine the ages and compositions of extragalactic clusters.

A study of 10 clusters in the Large and Small Magellanic Clouds (LMC and SMC) indicates compositions of about 80% solar metallicity for most LMC clusters and considerably lower metallicities for the SMC and some LMC clusters. Deviations between the fit and the observations show two problems. One is that there are too few calculated stars in the post main sequence band just after core-hydrogen exhaustion. This may be caused by higher-order convective processes such as convective overshoot. The other feature is that there appears no evidence for late asymptotic giant branch evolution for these stars. Instead a maximum luminosity is reached. Apparently these stars encounter envelope instability which leads to the ejection of outer layers and planetary nebula formation rather than evolution toward a carbon deflagration supernova.

Direct Radiative Neutron Capture in the r-Process

Reliable estimates of neutron capture cross sections of nuclides far from the line of stability are needed to understand rapid-neutron-capture (r-process) nucleosynthesis, since detailed stellar models of

the r-process predict too few neutrons to sustain (n,γ) - (γ,n) equilibrium. Neutron capture cross sections have been calculated with the Hauser-Feshbach statistical model. Near the r-process path, however, the reaction Q values are only ~ 1 -2 MeV and the level density is too low for the statistical-model assumptions to be valid. Direct radiative capture may therefore be more important. Direct-radiative neutron capture rates for r-process nuclei have been calculated with the Lynn and Lane model under the assumption of pure shell model final states. The resultant cross sections are largest near the neutron closed shells and hence should affect calculations of r-process abundance peaks.

Energy Deposition in Intermediate-Energy Proton Reactions

The reaction mechanism of intermediate-energy nucleons with complex nuclei is still poorly understood. The two major models, Intra Nuclear Cascade, (INC), and Preequilibrium (PE) predict different yields for proton spallation of light nuclei, $12 \leq A \leq 28$. Such reactions are important in the understanding of the origin and propagation of cosmic-rays, as well as for space radiation effects in satellite semiconductor devices.

A study of product yields, energy spectra, and angular distributions uses 100 to 200 MeV protons from the Indiana cyclotron incident on ^{27}Al and ^{28}Si . The ^{27}Al data have been analyzed and agree with the PE model predictions, but disagree with the INC results. This difference with the INC model is probably due to the neglect of the hole energy in the residual nucleus once a cascade nucleon has been excited above the Fermi sea and ejected. Thus, the deposition energy

in the INC model may be underestimated. These results diminish the estimates of contributions of secondary reactions to the observed cosmic-ray isotopic anomalies, and may affect conclusions concerning the origin of the anomalies.

ATOMIC PHYSICS

Beam-foil Spectroscopy

A recently initiated beam-foil spectroscopy activity at the LBL Super-Hilac involves measurements of X-ray and UV transition energies, and of selected lifetimes of highly stripped ions ($Z \geq 26$) containing 1 to 10 electrons (hydrogen- to neon-like configurations). Of particular interest are the lowest L-shell transitions with a change of the principal quantum number by zero or one. The purpose of these experiments is to test the theory, i.e., accurate multiconfiguration calculations which include relativistic and quantum electrodynamic effects. The measurements are also of interest to Laboratory programs concerned with high temperature and density plasmas.

Two new high resolution spectrometers have been constructed for this program. One is a Johann geometry crystal spectrometer for X-rays above 1.5 keV. The resolution of this crystal spectrometer depends on the crystal but values of $\lambda/\Delta\lambda$ near 10^4 have been attained. The other is a grating spectrometer, which uses a micro-channel-plate and reticon to provide active multi-channel readout. This instrument is designed for UV radiation between 10 and 1000 Å.

The first experiments with iron and xenon beams are being analyzed. The goal is to establish energy levels of Ne-like xenon (10 electrons) and H- and He-like iron in order to verify recent measurements of the ground state Lamb shift in hydrogen-like Fe and to measure the fine structure splitting of the $^2P_{3/2,1/2}$ levels in H-like Fe, which have been reported to have an anomalous value.

Z-pinch Plasmas

The ZAPP facility is used to study high-temperature high-density plasmas in the laboratory with particular emphasis on radiation from highly-stripped ions. The results are important for weapon physics, atomic collision phenomena, radiation transport and spectroscopy of high-Z ions.

Time resolved spectra of Si, P and Ar ions at temperatures in the neighborhood of 100-150 eV have been obtained in a grazing-incidence spectrometer equipped with gated microchannel plates. In this temperature range 5 to 12 electrons are stripped from the neutral atom. The observed spectra in the 100-400 Å range are being compared with a newly developed calculation of line intensities to check theoretical excitation cross sections.

ZAPP also produces plasmas at temperatures up to 1.5 keV and electron densities above 10^{21} cm^{-3} . Crystal spectrometers are used to study the temporal and spatial dependence of the 1-4 keV X-rays emitted by the plasma. Several features in these spectra are sensitive to temperature, density, opacity and the transient nature of the plasma, i.e., whether it is ionizing or recombining. For low Z atoms ($Z \leq 18$) the observed spectra come from atoms with 1, 2 or 3 electrons. Calculations of the emission spectra are compared with the data, and plasma temperatures and densities are determined. For krypton the observed spectra are due to atoms with 8 to 12 electrons. Modeling of these plasmas is more difficult. Plasma temperature and density are determined with a low Z impurity. An L-shell model to explain the ZAPP spectra is being developed. Preliminary results indicate the importance of dielectronic processes in modeling the plasma.

Channeling Radiation

When a charged particle passes through a crystal along a major planar or axial direction of the crystal, it undergoes periodic motion in the transverse direction and radiates. If the particle is highly relativistic, the radiation is focussed into a narrow forward cone and shifted upward in energy by relativistic contraction and by the Doppler effect. The result for electron or positron beams of a few tens of MeV is a very intense, nearly monochromatic, highly directional, easily tunable, and polarized photon beam in the hard X-ray energy region (tens to hundreds of keV). Such beams have many potential applications, and the study of the characteristics of this channeling radiation itself yields information about the properties of the crystal in which it is made.

This new type of radiation was first observed in 1978. Since that time its properties have been studied in detail. Recent measurements used crystals of Si, Ge, W, diamond (both with and without nitrogen platelet impurities), LiF, LiH, NaCl (both with and without quenched-in defects), NaF, gold-doped silicon, and BeO. The quality and quantity of the data have improved as better techniques for tuning electron and positron beams of lower divergence have been developed.

Positronium

Last year the feasibility of producing low-energy positron beams at the electron Linac was established. The intensity of these low-energy positron beams is much greater than can be obtained with radioactive positron emitters.

The low-energy positron beam can be used to form positronium, the fine-structure of which can then be studied by Doppler-free two-photon laser excitation. A beam line for this experiment and the timing of the laser and positron pulses have been tested.

MATERIALS SCIENCE

Positrons

The availability of low energy positrons at the electron Linac was discussed in the preceding section. The development of techniques for positron production and of apparatus for positron experiments has continued.

An experiment is being set up to measure the properties of materials at surfaces using the positron beam and two-dimensional angular correlation of annihilation radiation. This experiment aims to measure the electron momentum distributions of states at or near the surface of the material. An array of detectors determines the positions where the annihilation radiation gamma-rays originate so that the angle between the two gamma rays can be calculated. The detector arrays are the NaI scintillator arrays of the Anger camera which in the past has extensively been used in medical imaging. The angular correlation system is set up and awaits the completion of a beam line and sample chamber.

Measurements of bulk properties of materials with positrons from a radioactive source were continued on uranium oxides, radiation damaged metals, and metallic glassy materials to investigate the temperature dependence of positron trapping at defects in the material at low temperatures.

DEVELOPMENT PROJECTS

Nitrogen and Argon Exchange in Tissue

The cooperative effort with the Naval Medical Research Institute to develop better decompression tables for deep sea divers is continuing. In these experiments short-lived radioisotopes that serve as tracers are produced at the Linac. Last year's report mentioned an experiment in which divers breathed air tagged with radioactive nitrogen and radioactive argon. The analysis of the data shows that nitrogen and argon, which have about the same solubility in blood and tissue, exchange at different rates.

Neutron Diagnostics of Fusion Plasmas

Techniques for the measurement of neutron energy and intensity, some originally developed for nuclear physics experiments, have been improved and adapted to the determination of ion energy in magnetically confined deuterium plasmas. Improvements in spectrometer energy resolution as well as in the data rate capability of the detectors and electronics now permit neutron energy measurements (and consequent plasma temperature determination) in intervals as short as 50 ms. This allows neutron measurements to be used as a means of studying the temporal development of ion temperature during plasma buildup and heating as well as during plasma decay at the end of a confinement cycle. Recently a computer simulation has been developed to study the feasibility of using measurements of the energy spectra of fusion reaction products (including neutron spectra) as a tool in the determination of the ion speed distribution in plasmas which are not in

thermal equilibrium. Most plasmas in experiments operating now or in the near future are heated by microwave absorption and/or neutral beam injection so that their speed distributions are non-maxwellian and the determination of the shape of the distribution at high speeds is important.

Diagnostics Development for Electron Accelerators

Propagation of high current relativistic electron beams in vacuum and in various gases at pressures up to one atmosphere is being studied at the ETA and ATA electron accelerators. Knowledge of the beam energy, divergence, and current density profile is important to the understanding of instabilities which interfere with beam propagation and transport. A technique in which characteristic X-rays are observed when the beam passes through a thin high-Z foil, or a gas doped with small amounts of Xe or Kr, has been developed for some of these measurements. An X-ray pinhole camera coupled to a gated TV camera has been constructed for time resolved measurements of an electron beam profile during propagation. The camera is currently being evaluated on a 10 kA, 5 MeV beam.

Breakdown of Gases by Microwave Pulses

Studies of the breakdown of air and other gases by microwave fields, have been reported in the literature for the cw and long-pulse ($\geq \mu\text{s}$) case, and the results agree well with theoretical predictions. However, there have been few experiments with microwave pulses shorter than 1 μs , and there are no published results for pulses shorter than 100 ns. Models predict that such short pulses can

propagate through gases at considerably higher peak power levels than can cw or long-pulse beams, but the validity of the theory is doubtful for very short pulse lengths and high power levels. There is current interest in the power levels at which short pulses can be transmitted through the atmosphere before breakdown occurs because short pulses of microwave energy are known to damage solid-state electronics (e.g. missile guidance systems).

Two pulsed microwave systems, which use the spare modulator and S-band klystron of the 100-MeV Linac, can serve to study the breakdown of air and other gases. In one system the klystron drive is gated to produce pulses with up to 20 MW of peak power, rise times of 50 ns, and pulse widths of 200 ns. Some preliminary experiments on air breakdown have been performed in a waveguide at pressures between 400 Torr and 100 mTorr (corresponding to altitudes of 6 km to 65 km) to determine the energy that can be propagated before the pulse is attenuated by the plasma which forms.

In the second system microwave pulses are generated by a modified version of a resonant-cavity/switch system which was developed several years ago. The present version of this pulse generator produces pulses with peak power of 100 MW, 4 ns rise time and 15 ns width. The transmission of these pulses through an air-filled waveguide section at 10.5 Torr was measured. An attempt is being made to improve the pulse-shape and amplitude stability.

The aim of the work has been to establish a facility for performing experiments, to identify necessary improvements in techniques and apparatus, and to provide high-power microwave pulses for other groups. The initial results have extended the range of single-pulse

breakdown to shorter pulses by an order of magnitude, and they agree with recent calculations.

X-ray Diagnostics for NLTE Experiments

Measurements of the spectrum and flux of X-rays are needed to diagnose extremely hot plasmas which cannot be characterized by a single temperature. Information about electron collision rates, ionization states and radiation transport in the plasma can be obtained from high-resolution X-ray emission spectra. Such measurements are also important as tests of the codes used throughout the laboratory to predict the behavior of plasmas. Energy selectivity is important in these experiments, since line radiation must be observed against a continuous background. Energy selectivity has been achieved by using bent crystal spectrometers and filtered flux monitors.

Two bent crystal spectrometers were designed for use on Non-Local Thermodynamic Equilibrium (NLTE) experiments at the Nevada Test Site and ZAPP. The first spectrometer was designed to study lines from levels populated by electron collisions in a hot plasma. This spectrometer had 12 eV resolution and used an iridium plated mirror to prevent spectral distortion from higher order diffraction of the mica crystal. The measured spectrum agreed qualitatively with code predictions. The second spectrometer was designed to observe dielectronic satellite lines emitted by various elements in the range from neon to argon. These measurements are used to diagnose the electron density and temperature of the ZAPP plasmas. To cover such a range of X-ray energies with good resolution, a spectrometer was designed to accept a variety of diffraction crystals and alternative

locations for film or other X-ray detectors. A discrepancy in the code calculations was discovered in attempting to predict observed satellite line intensities.

Recently measurements of the X-ray fluence at discrete energies were needed to diagnose the conditions in hot, dense plasma experiments at the Nevada Test Site. It was necessary to sample a small fraction of the large flux produced by this plasma. The time variation of these emissions was also important in diagnosing the plasma. Fast time response and low sensitivity make the vacuum X-ray diode (XRD) a good choice for use in this diagnostic. Since the sensitivity of the XRD varies with the inverse cube of X-ray energy, a band pass filter was needed to get energy selectivity. Two types of filters were used in these experiments. The first employed a scatterer and filter to select the energy. The filter thickness was chosen so that an edge in the X-ray transmission passes the appropriate band of X-ray energies. The second approach used a fluorescing material in the X-ray flux which sets the low energy edge of the pass band. A filter edge was selected to set the high energy limit of the pass band. This approach is sensitive to lower X-ray fluences. These measurements confirmed code calculations of the intensity of continuum emission from the plasma.

SCIENTIFIC STAFF

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Members of the staff are serving on several national committees:

American Physical Society

Committee on the Status of Women in Physics. L. F. Hansen

Committee on the International Freedom of Scientists.

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Department of Energy

Nuclear Data Committee. R. C. Haight

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Fusion, Basic Energy Sciences. R. C. Haight

National Research Council

Panel on Basic Nuclear Data Compilations. C. H. Poppe

Lawrence Berkeley Laboratory

Superhilac Executive Committee. H. M. Blann

Members of the staff served on several conference committees:

Advisory Group Meeting on Basic and Applied Problems of Nuclear

Level Densities. R. C. Haight, Program Committee

Workshop on Microscopic Approaches to Nucleon-Nucleus Scattering.

C. H. Poppe, Workshop Chairman

Members of the staff were invited to give papers at national or international meetings.

IEEE Conference on the Application of Accelerators in Research and Industry, 1982, Denton, TX. "Radioactive Ion Beams for Studying Astrophysical Nuclear Reactions". R. C. Haight

IEEE Conference on the Application of Accelerators in Research and Industry, 1982, Denton, TX. "Low-Energy Positron Production at the Livermore Linac". R. H. Howell

IEEE Conference on the Application of Accelerators in Research and Industry, 1982, Denton, TX. "Tritium Target Performance at RTNS-II". Dale Heikkinen

AAAS Symposium on Low-Energy Positron Beams, 1983, Detroit, MI. "The Livermore Positron Program". R. A. Alvarez.

Third Symposium of the Chilean Physical Society, 1982, Valparaiso, Chile. "Test of Microscopic Model Potentials Over Wide Mass and Energy Ranges". L. F. Hansen

Pacific Conference on Chemistry and Spectroscopy, 1982, San Francisco, CA. "Detection of the K-Series from the Elements Be through Al". D. Dietrich

LANL Workshop on Highly Ionized Atoms, 1982, Los Alamos, NM. "Spectroscopy in High Z, Highly Ionized Systems". D. Dietrich

Fourth APS Topical Conference on High Temperature Plasma Diagnostics, 1982, Boston, MA. "Advanced Neutron Diagnostic Technique in Magnetic Fusion". D. R. Slaughter

Advisory Group Meeting on Basic and Applied Problems of Nuclear Level Densities, 1983, Brookhaven, NY. "Applied Uses of Nuclear Level Densities". R. C. Haight

University of Washington Symposium of Accelerator Operations, 1982 Seattle, WA. "A Survey of E-Division Accelerators at the Lawrence Livermore National Laboratory". I. D. Proctor

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BUDGET AND MANPOWER

In the following table budgeted costs are given in thousands of dollars (\$... K) and number of people as "Full-Time Equivalent" (FTE); these figures are for the 1983 fiscal year (FY83), which does not completely coincide with the report period covered in this report. The FTE's are averaged for the fiscal year.

Most of the funding of the E-Division Research is provided by the Division of Military Applications (DMA) of the Department of Energy (DOE). Other sources of funds from DOE are the Office of Fusion Energy (OFE), Basic Energy Sciences (BES), and Nuclear Physics Research (NP). There are additional small projects including one supported by the U.S. Navy (USN).

Since February 1982 the operations of RTNS-II have been supported in part by the government of Japan. This support amounts to about \$2000 K per year and is in addition to the \$2200 K shown in the following table.

AREA OF RESEARCH	SOURCE OF FUNDS	\$K	FTE
Nuclear Cross Sections and Integral Measurements	DOE-DMA	1800	13
Nuclear Modeling and Reactions	DOE-DMA	2000	15
Atomic and Plasma Physics	DOE-DMA	1500	13
Slow positrons, channeling radiation, electro-fission astrophysics	DOE-DMA	800	7
Hydrogen and Helium Production	DOE-BES	200	2
Plasma Diagnostics	DOE-OFE	200	2
Electron Scattering	DOE-NP	70	0.5
Radiation Damage (RTNS-II)	DOE-OFE	2200	20
Decompression Sickness	USN	30	0.3

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APPENDICES

Fig. 6

Time sequence of pinhole photographs showing neon x rays produced in a plasma with the ZAPP device. The exposure times and intervals between photographs were 2 ns. The time direction is to the right; the last frame is time-integrated.

ZAPP Upgraded

Our z-pinch facility (ZAPP, for Z-pinch Atomic Physics Project)² has been upgraded by the addition of several new diagnostic instruments. ZAPP was designed to study in detail the radiation emitted by very hot, dense plasmas. A z pinch (z being the axial direction) is a cylindrical implosion caused by the self-induced magnetic field of a heavy current flowing through a plasma.

The ZAPP device consists of a large capacitor bank (52 kJ maximum) for storing electrical charge, fast electrical switches, and a vacuum chamber into which we can inject a hollow cylindrical puff of gas through an annular slit centered in the face of a flat electrode. The gas crosses a gap of about 1 cm to a ring-shaped electrode, which is pulsed to a high voltage before the gas has time to fill the center of the puff. A heavy current from the capacitor bank ionizes the gas and then implodes it by interaction with its self-generated magnetic field. Since the initial plasma is hollow, the final forces opposing the implosion are reduced, and the plasma can reach higher densities and temperatures than those in previous z-pinch devices.

At the ZAPP facility, we can consistently produce argon plasmas with electron temperatures of 1 keV and a density of 10^{22} electron/cm³, a regime that until recently has been very difficult to achieve in the laboratory. These temperature and density conditions significantly affect the populations and lifetimes of the electronic states in the plasma. Our experimental studies of

these plasmas have possible applications in fields as diverse as astrophysics and laser fusion.

We use a variety of techniques to obtain information on plasma conditions and atomic radiation in the ZAPP device, including crystal, normal-, and grazing-incidence spectrometry, pinhole and Schlieren photography, interferometry, and Thomson scattering.

Last year, we built and added to ZAPP three diagnostic instruments that incorporate a microchannel plate (MCP) camera. In the MCP, incident photons produce an electron cascade across a voltage in a narrow channel. The amplification thus achieved makes it a highly sensitive photon detector. The new diagnostic instruments are a crystal x-ray spectrometer, a pinhole camera, and a grazing-incidence spectrometer. Together, they give us the ability to analyze photon emission with high spatial, spectral, and temporal resolution in the ultraviolet and x-ray regions of the electromagnetic spectrum.

We independently tested the MCP camera used in these instruments to determine its sensitivity and limits of spatial and temporal resolution. So sensitive are MCPs that they have been shown to be capable of counting individual photons. Under these conditions, sensitivity is limited only by the MCP's quantum efficiency. This represents an increase of two to three orders of magnitude over ordinary photographic film. We tested the camera's spatial resolution using a grating spectrometer and a cold cathode line source, achieving a resolution of less than 50 μm at the detector. Temporal resolution was tested

with an 80-ps laser pulse. Although the test was limited by the pulse power supply used to activate the MCP, resolution was much better than 1 ns.

Figure 6 shows a typical result obtained from the MCP diagnostics, in this case a time sequence of x-ray photographs of a neon plasma imploded with the ZAPP device. (The time direction is to the right.) The frames were exposed at intervals of 2 ns; the exposure time for each was 2 ns. The last frame is time-integrated. Simultaneous measurements of the x-ray and ultraviolet spectra with other MCP devices enable us to determine the temperature and density of the plasma as it heats and cools.

With the ZAPP device, we can also inject a mixture of gases in the gas puff. For complicated plasmas, the radiation from a selected minor constituent provides a "fingerprint" that indicates temperatures and densities. With this capability and the new MCP diagnostics, we are advancing our understanding of the interactions of ions, electrons, and photons in dense plasmas.

Fig. 7

Dr. Toshiyuki Iida of Osaka University, Japan, preparing fiber-optics material for the measurement *in situ* of light transmission in the RTNS-II target room. Dr. Iida is the first Japanese scientist assigned to work at RTNS-II. The 50-cm-diameter target is mounted on the red cone forming the end of the deuteron beam line.

Joint U.S.-Japanese Neutron-Source Program

Realizing the promise of fusion power will require many advances in materials science. Foremost is the need to understand the response of materials to irradiation with 14-MeV neutrons (those produced in fusion reactions). The Rotating Target Neutron Source II (RTNS-II), a materials test facility at LLNL dedicated to fusion materials research, has operated since early 1979 in support of the U.S. fusion power program. Although the facility contains two separate neutron sources, funding constraints made it possible to operate only one source.

These constraints were offset early in 1982, when the governments of the U.S. and Japan reached an agreement under which Japan contributes about \$2 million per year to RTNS-II operations and shares the neutrons available for experiments. This arrangement will effectively double the RTNS-II budget, enabling us to start up the second

neutron source. The resulting increase in operating hours and improved performance will triple the annual neutron output.

At the RTNS-II, we produce neutrons by accelerating deuterium ions to 400 keV and transporting the beam to a rotating target coated with metal tritide (Fig. 7). The deuterons in the beam fuse with the tritium in the target to create 14-MeV neutrons. To dissipate the enormous power density deposited by the deuteron beam, we rotate the target at 5000 rpm. Early operations were done with targets 23 cm in diameter; in November 1981, we increased target diameters to 50 cm to allow the use of higher beam currents and to improve the target lifetime.

Japan's fusion technology program is developing rapidly. The joint U.S.-Japanese effort will enable the two countries to merge their programs in the area of fusion neutron effects and

will give Japan immediate access to an advanced experimental facility. Japanese scientists are now in residence at RTNS-II, conducting experiments and working with U.S. colleagues. Japan is also developing a substantial postirradiation test laboratory at the facility. The laboratory, which will eliminate most shipping time and unnecessary handling of radioactive materials, will be used jointly.

A bilateral RTNS-II Steering Committee charts the course of the experimental program and the general development of RTNS-II. Early in 1982, the committee held its first meeting at Monbusho, the Tokyo headquarters of the Japanese agency that supports the RTNS-II research, to plan for the coming year.

How Old is the Universe?

Our measurement of the neutron-capture cross sections for two rare isotopes of osmium provides necessary data for the determination of the age of the universe. These new data imply an age of 17 ± 3 billion years, which, when compared with the limit set by a recent determination of the Hubble time, has important implications for cosmology.

According to the currently accepted view, the universe began with the Big Bang, a singularity in time and density.¹ Some 1.5 ± 0.5 billion years (b.y.) later,² the first galaxies, including our own Milky Way, were formed out of the debris of that primordial event. A time period Δ elapsed between the formation of the Milky Way and the formation of our solar system. It is well established that our solar system condensed about 4.7 ± 0.1 b.y. ago out of interstellar material ejected from preceding supernovae (exploding stars) in the Milky Way.³

The age of the universe thus is given by the relation $A_U = 1.5 + \Delta + A_s$ (where $A_s = 4.7$, the age of the solar system, and all the quantities are expressed in billions of years). In estimating the age of the universe A_U , we must find a measure of the period of nucleosynthesis Δ , when the matter composing the solar system was being processed in the stars. Therefore, the age of the galaxy $A_G = \Delta + 4.7$. Figure 1 shows the relative time scales graphically.

The key to determining Δ is provided by nuclear dating techniques based upon isotopic abundances. These techniques depend, in turn, upon an understanding of the processes that formed and/or destroyed the present elements and upon a knowledge of the relative abundances and the decay rates (half-lives) of the nuclear species used in dating. The basic mechanisms for the formation of the elements were first described in the classic paper of Burbidge *et al.* in 1957.⁴ Figure 2 shows these mechanisms on a chart of the nuclides. Elements heavier than iron (for which the binding energy per nucleon reaches

a maximum) are formed by the successive capture of neutrons, which can proceed either slowly (the s process) or rapidly (the r process). Although the neutron source has not been determined unambiguously, it is thought that the reaction

plays the dominant role.⁵ The s process proceeds along the valley of beta stability (see Fig. 2) and terminates at bismuth; the s process takes place primarily in helium-burning stars, which are relatively long-lived. The r process departs substantially from the valley of stable nuclei and is responsible for the production of the elements heavier than bismuth (see Fig. 2); the r process occurs primarily in supernovae.

The most widely used nuclear-dating method based upon the r process is the uranium-thorium technique.⁶ Using this method, the production ratios for

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of the chronometer nuclei depends upon the assumption, which is hard to test, that each of the progenitors of the chronometer nuclei was present in equal abundance. Second, the half-lives of the chronometer nuclei are comparable to (and not much longer than) their age; any uncertainties in their determination thus multiply exponentially.

In contrast to the *r* process, the *s* process rests upon a firmer theoretical footing, as we will show below. We have used a model based upon the *s* process to make a new determination of the age of the universe.

The Rhenium-Osmium Clock

About twenty years ago, it was suggested by Clayton⁷ that the uncertainty in the radiogenic age determination of the universe might be reduced by using as a nuclear chronometer an *s*-process nucleus. The stable light isotopes of the heavy metal osmium—osmium-186 and osmium-187—are pure *s*-process nuclei (being shielded from the *r* process by stable tungsten-186 and long-lived rhenium-187, respectively) and are found in a relatively undisturbed state in primordial meteorites. Further, osmium-187 can result from the beta decay of rhenium-187, which has a half-life of about 43 b.y., far longer than the age of the universe (see Fig. 2 inset).

An *s*-process chronometer does depend, however, on the validity of the "local" assumption that the product $N\bar{\sigma}$ is constant for adjacent *s*-process nuclei, where N is the *s*-process equilibrium abundance of a given nuclear species and $\bar{\sigma}$ is the Maxwellian-averaged neutron-capture cross section of that species at the temperature T appropriate to the stellar site of the *s* process (commonly accepted as kT equal to about 30 keV, where k is the universal gas constant). This assumption is well supported for the isotopes of strontium, zirconium, tin, and samarium.⁸ Because this assumption is likely to hold even more rigorously for the isotopes of osmium, which are far from any nuclear shell closure, little uncertainty should result from its use.

The determination of the duration of nucleosynthesis Δ requires several steps (see box on p. 4). We wish to establish the original *s*-process abundance of osmium-187. Because a portion of the osmium-187 originated by beta decay from the *r*-process nucleus rhenium-187, we have to find the ratio R of the abundance of the radiogenically produced osmium-187 to that of its parent nucleus, rhenium-187 (see Eq. (2) in box).

The isotopic abundance ratios pertinent to the determination of the value of R are obtained from meteoritic data (which are uncertain to $\pm 10\%$).⁹ But the creation and destruction rates of osmium-187 in a stellar neutron flux are determined by the relative neutron-capture cross sections for osmium-186 and osmium-187. Therefore, in order to determine Δ , we had to measure the ratio of the neutron-capture cross sections ($\bar{\sigma}_{186}/\bar{\sigma}_{187}$).

The value of the latter ratio then must be multiplied by a correction factor f to account for the fact that osmium-187 nuclei in a stellar environment exist in a low-lying excited state (at about 10 keV) as well as in their ground state. (Osmium-186 and rhenium-187 do not have any excited states below 100 keV.) We use the measured value of $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ and a calculated value of f to obtain R . We then determine Δ from R using Eq. (3) in the box.

Finally, the value of Δ also depends upon the supernova rate in the galaxy λ_A (see box). We used three alternative models to estimate λ_A : a uniform rate, an exponentially decreasing rate, and a single event.

Measurement of the Neutron-Capture Cross Sections

The key to our determination of the age of the universe was the measurement of the ratio of the neutron-capture cross sections for osmium-186 and osmium-187.¹⁰ This measurement required sufficiently massive and highly purified samples of these two rare isotopes. The measurements were carried out at LLNL; the samples, produced by a one-and-a-half-year effort at the Oak

The Determination of Δ Using the Rhenium-Osmium Clock

The rhenium-osmium clock depends upon the following principle. If we consider what the nuclear abundances were at the time of solar-system condensation (i.e., just after Δ , the period of nucleosynthesis), then the amount of osmium-187 that was produced by beta decay of rhenium-187 depends upon Δ . The amount of rhenium-187 produced by nucleosynthesis also depends upon Δ . Hence, if we can determine the ratio R of the amount of the daughter nucleus osmium-187 produced by beta decay to the amount of its parent rhenium-187, we then can extract a value of Δ . In doing this, we must account for the fact that osmium-187 also was produced and destroyed by the s process during nucleosynthesis.

If the s-process abundances of osmium-186 and osmium-187 are denoted by N_s^{186} and N_s^{187} , respectively, and the radiogenic component of osmium-187 resulting from beta decay of rhenium-187 by N_{rad}^{187} , the total abundances of osmium-186 (N^{186}) and osmium-187 (N^{187}) are

$$N^{186} = N_s^{186}$$

and

$$N^{187} = N_s^{187} + N_{\text{rad}}^{187}. \quad (1)$$

Using the local assumption that $N_s^{186} \bar{\sigma}_{186} = N_s^{187} \bar{\sigma}_{187}$, where $\bar{\sigma}_{186}$ and $\bar{\sigma}_{187}$ are the Maxwellian-averaged neutron-capture cross sections for osmium-186 and osmium 187, respectively, together with Eq. (1), we then can express the ratio of N_{rad}^{187} to its parent rhenium-187 abundance N_{Re}^{187} as

$$R = \frac{N_{\text{rad}}^{187}}{N_{\text{Re}}^{187}} = \frac{(N^{187}/N_{\text{Os}}) - f(\bar{\sigma}_{186}/\bar{\sigma}_{187})(N^{186}/N_{\text{Os}})}{N_{\text{Re}}^{187}/N_{\text{Re}}^{186}} \times \frac{N_{\text{Os}}}{N_{\text{Re}}}, \quad (2)$$

where N_{Os} and N_{Re} are the elemental abundances of osmium and rhenium. This value of R is for the time of solar system condensation, with all the isotopic abundances evaluated at that time. (The cross-section ratio $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ measured in the laboratory must be multiplied by a correction factor f to account for the fact that in a stellar environment osmium-187 nuclei exist in both ground and excited states).

If we assume that the r-process nucleosynthesis that produced rhenium-187 began at a time Δ before the condensation of the solar system and decreased exponentially, the rate of decrease λ_A is a measure of the supernova rate in the galaxy. If λ_B is the beta-decay rate of rhenium-187, we then can use the Bateman equations for radioactive growth and decay to express the ratio R at the time of solar-system condensation as

$$R = \frac{N_{\text{rad}}^{187}}{N_{\text{Re}}^{187}} = \left\{ \frac{\lambda_A - \lambda_B}{\lambda_A} \exp(\lambda_B \Delta) \times \frac{1 - \exp(-\lambda_A \Delta)}{1 - \exp[-(\lambda_A - \lambda_B) \Delta]} \right\} - 1. \quad (3)$$

This model has two extreme cases: (1) sudden synthesis, a single supernova event for which λ_A approaches infinity and the value of R in Eq. (3) becomes approximately equal to $\lambda_B \Delta$ ($\lambda_B \Delta$ is much smaller than unity), and (2) uniform synthesis, for which λ_A approaches zero and R becomes approximately equal to $\lambda_B \Delta/2$. We have chosen a "happy medium" value for λ_A , assuming that the supernova rate was higher when the galaxy was younger. This assumption corresponds to the early existence of a larger number of massive stars than now; such stars are more likely to end their existence as supernovae, and to do so more quickly, than less massive stars. We have used a value of 0.43 for λ_A^{-1} . (This value has also been used to determine Δ by the uranium-thorium method.)*

We obtained the isotopic abundance ratios in Eq. (2) using data from meteorites and a rhenium-187 half-life of 43 b.y. Extrapolated back to the time the solar system condensed, these data give a value of 0.0125 ± 0.0006 for $N_{\text{Os}}^{187}/N_{\text{Os}}$, 0.0159 for $N_{\text{Os}}^{186}/N_{\text{Os}}$, and 0.65 for $N_{\text{Re}}^{187}/N_{\text{Re}}$. (The geochemical uncertainties for the last two quantities are negligible.) For the elemental abundance ratio $N_{\text{Os}}/N_{\text{Re}}$, we used the value 13.1 ± 0.6 , obtained from an analysis of C1 carbonaceous chondrites only.[†] This value excludes the slightly lower values obtained from other types of meteorites that are thought to be less ancient.

The remaining quantities critical to the determination of Δ are the measured cross-section ratio $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ and its correction factor f .

*W. A. Fowler, in *Cosmology, Fusion, and Other Matters* (Ed., F. Reines), Colorado Assoc. Univ. Press, Boulder, Colorado (1972).

[†]S. E. Woosley, private communication (1979).

Ridge National Laboratory (ORNL), consisted of 3.278 g of 78.39% isotopically pure osmium-186 and 2.959 g of 70.96% isotopically pure osmium-187.

Our experiment was performed at the neutron time-of-flight facility at the LLNL Electron-Positron Linear Accelerator. Figure 3 is a schematic diagram of the experimental apparatus. The experiment consisted of irradiating the isotopic samples with neutrons and detecting the gamma rays emitted by the neutron-capture process. Neutrons were produced by irradiating a water-cooled tantalum target with a pulsed 115-MeV electron beam from the accelerator. The

neutron energies were determined by their flight times down an evacuated, 15-m-long collimated tube to the samples (see Fig. 3). The energy profile of the neutron flux was measured by scattering the neutrons from a thin graphite foil located on an adjacent flight path into a nearby lithium-6 glass scintillation detector. This detector also served as a neutron monitor for cycling the osmium samples.

The samples were enclosed in light-weight beryllium containers. (Because the samples were not 100% pure, the other osmium isotopes present were measured as well.) We used a pair of

Fig. 3

Schematic diagram of the neutron-capture cross-section experiment. (a) Neutrons were produced in a water-cooled tantalum target struck by a pulsed 115-MeV electron beam from the LLNL Electron-Positron Linear Accelerator. (b) The osmium samples were cycled into position in the collimated neutron beam between two deuterated-benzene (C_6D_6) scintillation detectors that measured the gamma rays emitted by neutron capture. (c) The neutron flux was monitored on a separate flight path with a lithium-6 glass scintillator. (Figure adapted from Ref. 10.)

Fig. 4

Average neutron-capture cross sections for osmium-186 and osmium-187 as a function of neutron energy, as measured with the apparatus shown in Fig. 3. From these data, the Maxwellian-averaged cross sections for a kT of 30 keV were obtained; their ratio is a necessary parameter for determining the ratio of the s-process abundance of osmium-187 to the radiogenic component of osmium-187 resulting from the beta decay of rhenium-187. (Figure adapted from Ref. 10.)

one-litre deuterated-benzene liquid scintillators to detect the neutron-capture gamma rays. (Deuterated material was used to eliminate the severe background that would have resulted from the 2.2-MeV gamma rays produced when neutrons are captured by ordinary hydrogen.) They were positioned close to the sample in order to subtend a large solid angle.

Figure 4 shows the neutron-capture cross sections of osmium-186 and osmium-187 measured in our experiment. Using these data, we obtained the Maxwellian-averaged cross sections for kT equal to 30 keV, the temperature appropriate to the stellar site of the s process. The value of the resulting ratio $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ was 0.48 ± 0.04 . (Similar measurements were subsequently made at the National Bureau of Standards at 25 keV using an iron-filtered neutron beam from a reactor¹¹ and at the electron linear accelerator at ORNL, another neutron time-of-flight measure-

ment.¹² These experiments gave values for $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ of 0.475 ± 0.075 and 0.478 ± 0.022 , respectively.) Thus, all three results are in excellent agreement.

We next applied the correction factor f to account for excited nuclear states in the stellar interior. This calculation requires as input parameters (among other things) the level spacings and spin distributions in the nuclei of osmium-187 and osmium-188, which result from neutron capture by osmium-186 and osmium-187, respectively.¹³ Some of the input data for this calculation came from another LLNL linac experiment.¹⁴ Figure 5 shows the curve representing f as a function of temperature. The value of f at kT equal to 30 keV (3.6×10^8 degrees) is 0.83. (This parameter does not depend strongly upon temperature for values reasonably near 30 keV).

The Duration of Nucleosynthesis

We next related the measured value of $\sigma_{186}/\sigma_{187}$ to a value for Δ , the duration of nucleosynthesis, using equations (2) and (3) in the box on p. 4. Figure 6 shows the results corresponding to the three models for the supernova rate in our galaxy.¹⁵ The available experimental data for $\bar{\sigma}_{186}/\bar{\sigma}_{187}$ were combined to give a value of 0.478 ± 0.018 (shown as the data point on the middle curve of Fig. 6), which corresponds to a value for Δ of 10.8 ± 1.2 b.y.

However, because of uncertainties in the value of f and in the half-life of rhenium-187 (which have not yet been included), we must increase the uncertainty in Δ . The uncertainty in f results from a discrepancy between two recent experimental determinations of the inelastic neutron-scattering cross section for osmium-187.¹⁶ The effect of the measurements is in one case to suggest an increase and in the other a decrease in the value of f used here, each by about 20%. Resolution of this uncertainty awaits a better measurement of the inelastic neutron-scattering cross section of osmium-187 at 30 keV.

Because it is very difficult to measure accurately, the half-life of rhenium-187 is also in some doubt. There is an effort

underway at LLNL¹⁷ to measure an accurate value for the half-life of rhenium-187 using nuclear-chemistry techniques. Because the beta-decay energy of rhenium-187 is very low (2.6 keV), the half-life will be determined indirectly by measuring the number of daughter osmium-187 atoms produced from the decay of rhenium-187. So far, five 1-kg batches of absolutely osmium-free perrhenic acid solution have been produced from which will be extracted the approximately 10^{13} atoms of the radiogenic daughter osmium-187 atoms which grow into each batch during a one-year period. This measurement necessitated the development of an entirely novel method of chemical separation, because the final product—osmium-187—must contain less than one atom of rhenium-187 in approximately 100 atoms of osmium-187 for the results to be significant, although the initial ratio was 10^{12} atoms of rhenium-187 for each atom of osmium-187. With the help of scientists at the National Bureau of Standards, a laser-microprobe mass analyzer will be used for the mass spectrometry of very small samples (i.e., less than a nanogram) of osmium.

A few other potential problems might be associated with the use of the rhenium-osmium clock. For example, the high temperatures and densities prevailing in a stellar interior might affect the rhenium-to-osmium beta-decay rate. The temperature effect would shorten, and the density effect lengthen, the half-life of rhenium-187. There is also an isomeric state of rhenium-186 (with a half-life of 2×10^5 years) that could short-circuit the s process to some extent, resulting in the production of some s-process rhenium-187.¹⁸ Finally, the value of the elemental abundance ratio of osmium to rhenium remains somewhat controversial. None of these qualifications, however, appears at this time to jeopardize our analysis seriously.

Incorporating reasonable uncertainties for the correction factor f and for the half-life of rhenium-187 into the uncertainty in our value for Δ , we obtain a "best" value of 10.8 ± 2.2 b.y.

Fig. 5

The correction factor f relates the ratio of the measured Maxwellian-averaged neutron-capture cross sections for osmium-186 and osmium-187 to the appropriate stellar conditions. For a temperature near 3.6×10^8 degrees ($kT = 30$ keV), typical of stellar conditions, the value of f is about 0.83.

The largest part of our uncertainty is associated with the determination of f . This result is significantly larger than the value of 6.1 ± 2.3 b.y. obtained with the r-process uranium-thorium method.

The Age of the Universe

Adding our value of Δ (10.8 ± 2.2 b.y.) to the age of the solar system (4.7 ± 0.1 b.y.) gives us an age for the galaxy of 15.5 ± 2.3 b.y. This number is concordant, but not comfortably so, with the value of 11 ± 3 b.y. obtained with the globular-cluster method.¹⁹ (This method attempts to date globular clusters, perhaps the oldest objects in our galaxy. Using the ratio of helium to hydrogen obtained from observations of the visible light from stars in these clusters, one can calculate the age of the galaxy from stellar models. This method depends upon assumptions

Fig. 6

The duration of nucleosynthesis Δ before the condensation of the solar system as a function of the ratio of the measured Maxwellian-averaged neutron-capture cross sections for osmium-186 and osmium-187. The supernova rate λ_A is represented by three alternative models: a uniform rate ($\lambda_A \rightarrow 0$), an exponentially decreasing rate $\lambda_A = (0.43\Delta)^{-1}$, and a single event ($\lambda_A \rightarrow \infty$). The data point represents the combined results of several measurements, including the one done at LLNL. The error bar includes the experimental uncertainties, but not those resulting from the values used for the half-life of rhenium-187 or for the correction factor f .

about stellar evolution and the primordial helium abundance, and is thus somewhat uncertain.) Far more encouraging are the recently reported spectral and photometric observations of two faint galaxies whose ages are estimated at between 15 and 18 b.y., making them the oldest objects observed to date.²⁰

Finally, adding 1.5 ± 0.5 b.y. to account for the time between the Big Bang and the formation of the galaxy gives us a value of 17 ± 2.5 b.y. for A_U , the age of the universe. To take account of additional uncertainties that cannot be explicitly evaluated at present, this uncertainty probably should be increased to ± 3 b.y.

Implications for Cosmology

If we assume the validity of Hubble's law, namely, that the greater the distance of an astronomical object the farther its radiation spectrum is shifted to longer wavelengths, then the observation of such objects indicates that the universe is expanding. The constant of proportionality in this relationship is called the Hubble constant, and its inverse the Hubble time T_H . If the universe had been expanding at a constant rate since its origin, T_H would equal the age of the universe. In other words, if Hubble's law is valid, T_H represents an upper limit for A_U . (It would equal A_U if the universe were not being decelerated by the mutual gravitational attraction of the matter it contains.) The most recent conventional value for T_H is 16.6 ± 1.7 b.y.²¹ This value (nearly the same as our value for A_U) implies

that little or no deceleration has occurred, which in turn implies that the universe is open and will expand forever (see the rust line in Fig. 7).

If the value of T_H were much larger than that of A_U , the universe would be sufficiently massive to be closed, eventually contracting upon itself, and finally ending its existence in a "Big Crunch," an event that may be thought of as a time-reversed version of the Big Bang (see the green line in Fig. 7). The near equality of T_H and A_U , in contrast, suggests that the universe will end "not with a bang but a whimper."

These arguments are based upon a model of the universe in which conventional ideas about gravitation hold, corresponding to a null value for the cosmological constant in Einstein's equations of general relativity. Recent evidence, however, suggests that T_H may be only about 10 b.y.,²² substantially *smaller* than the value of A_U that we have determined. This new value of T_H then would imply that at sufficiently large distances, objects in the universe are subject to a mutual repulsion, corresponding to a positive value of Einstein's cosmological constant (as represented by the gold line in Fig. 7). If substantiated, this result would be of supreme importance to cosmology, because the only alternative to mutual repulsion would be a

Fig. 7

Three scenarios for the evolution of the scale of the universe over time, for various values of the Hubble time T_H relative to the age of the universe A_U . The scenarios assume the validity of the Big Bang theory of the origin of the universe. The rust line, for T_H only slightly greater than A_U , represents an open universe that expands forever at a gradually decreasing rate. The green line, for T_H much greater than A_U , represents a closed universe that eventually contracts upon itself. The gold line, for T_H less than A_U , represents the possible evolution of a universe in which Einstein's cosmological constant is greater than zero, corresponding to a mutual repulsion of the objects in the universe at sufficiently large distances.

universe whose early history cannot be described by the Big-Bang model. Although few astrophysicists currently subscribe to either of these possibilities, they represent an exciting challenge that can be resolved only with further evidence.

Summary

We have made a new determination of the age of the universe based upon the use of the rhenium-osmium beta-decay clock. The crucial experimental element in this determination was our measurement of the neutron-capture cross sections for osmium-186 and osmium-187, in the energy range corresponding to stellar temperatures. The use of this clock gives us a value for the time elapsed between the formation of the Milky Way and the condensation of the solar system, the period during which the present matter of the solar system was undergoing nucleosynthesis in the interior of stars. Including reasonable assumptions and incorporating appropriate uncertainties, our determination of the age of the universe is 17 ± 3 billion years. This value, although significantly larger than the results of previous determinations, agrees with the age of recently discovered galaxies. It is greater, however, than the apparent limit set by the most recent determination of the Hubble time. This difference has implications of crucial significance for cosmology.

Key Words: age of universe; Big Bang; Hubble time; LLNL linear accelerator (linac); nucleosynthesis; neutron-capture cross section; osmium; radiogenic dating; rhenium-osmium clock; r process; s process; supernova.

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Neutron Diagnostics for Magnetically Confined Plasmas

We have developed spectrometers for measuring neutrons emitted by hot plasmas, enabling us to obtain data on mean ion energies and other parameters of interest in magnetic fusion experiments.

The principal goal of the Magnetic Fusion Energy (MFE) program is to confine, using magnetic fields, a hot plasma at densities and for times sufficient to generate a substantial amount of energy from thermonuclear fusion reactions.¹ The characteristics of the central plasma in fusion experiments

(such as mean ion energy, density, and scale length) are conventionally measured by detecting the hot atoms, ions, and charged reaction products escaping the plasma and by measuring the microwave, ultraviolet, and x radiation the plasma emits.² In a mirror-confined plasma, energetic ions may escape either along magnetic field lines at the ends of the plasma, or in the radial direction after charge exchange with a neutral atom. As confinement is

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improved, however, fewer particles escape the plasma radially, thus weakening these diagnostic signals.

Future MFE tandem-mirror experiments will produce high-density, large-radius plasmas in which the dimensions of the plasma will grow in relation to the mean free path for processes such as charge exchange. Under these conditions, central plasma ions or charged reaction products that escape radially may do so only after undergoing many collisions in the outer plasma and cool gas regions, making it increasingly difficult to interpret diagnostic data. (In tokamak experiments, in which the plasma is confined in a toroidal device that has no "end," all losses are radial so that improved confinement also weakens their signals substantially.) Finally, the high central temperatures generated in fusion experiments can completely ionize many of the impurity species (such as hydrocarbons, air, titanium, and iron) in the central plasma, reducing the utility of their characteristic atomic line radiation as a diagnostic feature.

The higher fusion rates that result from improved confinement, however, also produce higher yields of neutrons and gamma rays. These uncharged reaction products readily escape the central plasma and thus can provide information about its parameters. As our MFE program approaches its goals of producing break-even power, we must rely increasingly on uncharged reaction products and on ions that escape the ends of the plasma to characterize its parameters and to measure its fusion

power output. We have recently developed several diagnostic techniques based on the measurement of neutron emission from a magnetically confined plasma. We are currently applying these techniques to LLNL's Tandem Mirror Experiment (TMX) Upgrade and they will soon be used on Princeton's Tokamak Fusion Test Reactor (TFTR).

Neutron Generation in Magnetically Confined Plasmas

Nuclear fusion occurs when two light nuclei combine to release energy in the form of energetic reaction products. In MFE experiments, the reactions of interest are typically those of the heavy isotopes of hydrogen: deuterium plus deuterium ($D + D$), deuterium plus tritium ($D + T$), and tritium plus tritium ($T + T$). Table 1 shows several such reactions and the kinetic energies of their products. (Some reactions may take alternate paths, indicated by the percentage composition of their products in the table.) All of the reactions generate fast neutrons which readily penetrate dense plasmas without significant interaction.

The rate of a fusion reaction (and thus the neutron generation rate) depends on both the collision rate of the fast ions and their subsequent probability of fusion. The collision rate is proportional to the product of the densities of the reacting species (or to the square of density in the case of $D + D$ and $T + T$ fusion). The neutron generation rate per unit volume in a thermonuclear plasma thus is very sensitive to its density. Even more important, the probability of fusion is a very sensitive function of ion energy, since this quantity determines the probability that the two nuclei will approach each other closely enough to overcome their mutual electrical repulsion and fuse. Figure 1 shows the effective fusion or reactivity of the neutron-producing reactions in Table 1 as a function of the mean energy of the reacting ions. The very steep slope at energies from about 5 to 15 keV occurs in the region where fusion reactors are expected to operate.

Table 1 Reactions between light nuclei of interest in current magnetic fusion research. Kinetic energies of reaction products (in MeV) are given in parentheses. Composition of reaction products is given in percentages: D = deuteron, T = triton, p = proton, n = neutron, γ = gamma ray.

D + D	50%	T (1.0) + p (3.0)
	50%	^3He (0.8) + n (2.5)
D + T	$\sim 100\%$	^4He (3.5) + n (14.1)
	10^{-5}	^5He + γ (16.7)
T + T	100%	^4He (1.3) + 2 neutrons (~ 5 each)

Because reactivity, and thus neutron yield, increases roughly as the cube of the ion energy, neutron yield serves as a highly sensitive plasma thermometer. We have used an uncollimated detector to make accurate determinations of mean ion energy, a quantity closely related to the plasma temperature, by measuring both neutron yield and density in the end-plug plasmas of the TMX.³ Similar measurements are routinely made on plasmas confined in tokamak-like devices.

Determining Ion Energy Confinement Time

Hot ions in a magnetically confined plasma lose energy both by collisions with cooler ions and electrons and by charge-exchange reactions with cool gas. In many fusion experiments, ion energy loss is compensated by heating the plasma with neutral beams; that is, by injecting energetic neutral deuterium or hydrogen into the plasma. (Other techniques heat the plasma by inducing currents or by irradiating it with microwaves.) When plasma heating is terminated, the mean ion energy decays (cools) with a time constant τ_E . This time constant, which represents the energy confinement time, is an important plasma parameter. Because neutral deuterium beams used to heat a plasma also fuel it, termination of heating likewise causes the plasma density to decay according to a particle confinement time τ_p . Both decay processes reduce the fusion rate and hence the neutron yield. In a pure deuterium plasma, the time constant for decay of the neutron yield τ_N is related to τ_E and τ_p by

$$1/\tau_N = 2/\tau_p + \alpha/\tau_E,$$

where α is the logarithmic slope of the reactivity curve in Fig. 1. Since τ_p may be measured experimentally (by interferometry or neutral-beam attenuation methods) and α is already known, the decay of neutron yield τ_N , (i.e., when plasma heating is stopped) provides a very sensitive measure of τ_E .

Figure 2 shows some typical neutron-yield data obtained in the east end plug of the TMX using a liquid

Fig. 1

Fusion reactivity, expressed as the effective fusion cross section times velocity, rises very rapidly with ion energy because the speed of the ions brings the light nuclei closer together to overcome their mutual electrical repulsion. The three reactions shown produce fast neutrons. Because neutron generation rates are very sensitive to the mean ion energy or temperature of a hot plasma, neutron yield is a correspondingly sensitive plasma thermometer.

hydrocarbon detector. (With this type of detector, neutron intensity is determined from the rate of recoil protons generated by neutron-proton elastic scattering.) The inferred energy confinement time τ_E of about 5 ms agrees well with that derived from estimates of the plasma energy content and the power loss.⁴ Moreover, the neutron measurement is less ambiguous than power-balance calculations, which rely on estimated losses and inputs that are difficult to determine experimentally.

Imaging Neutron Emission from a Plasma

Because many thermonuclear plasmas have complex shapes and nonuniform density profiles, the speed distribution of their ions varies significantly with location. The spatial profile of neutron generation is helpful in studying these effects. It is also needed to determine total neutron generation

Fig. 2

Decay of neutron yield (red), which gives τ_N , and plasma line density (green), which gives τ_p , in a cooling magnetically confined plasma. The line density decay was measured with a beam-attenuation detector. The plasma was heated by neutral-beam injection for 25 ms in a TMX end plug. When injection is terminated, the density and mean ion energy of the plasma immediately begin to decline because of particle losses and cooling processes. Both effects sharply reduce the neutron generation rate. Unfolding the effects of density decay from the observed decline in neutron yield provides a very sensitive measure of the time constant for ion cooling, τ_E .

Our collimated MFTF-B spectrometer is distinctive both in its mechanical design and in the shield material used.

Fig. 3

Typical neutron pinhole camera, consisting of a thick polyethylene shield with a small-diameter hole. Conical entrance and exit apertures approximate ideal pinhole geometry. The neutron image is formed on a position-sensitive detector behind the pinhole. Water absorbs scattered neutrons. The camera is normally used 2 to 8 m from the source whose image is to be formed.

(fusion power) over the whole plasma. Neutron pinhole cameras and collimated detector arrays have been used for many years to form images of neutron emission from plasmas.

Figure 3 shows a typical pinhole camera design. The ideal conventional pinhole camera consists of a small hole in a very thin shield of opaque material. Because fast neutrons are very penetrating in all materials, however, there are no thin opaque shields that achieve the desired total opacity. In Fig. 3, the ideal pinhole is replaced by an opaque material (polyethylene) of substantial thickness, and the hole itself is a cylinder of significant length.

Because a neutron's mean free path in the shield material is typically large compared to the diameter of the hole, neutron pinholes have diffuse edges. In addition, the significant thickness of the hole causes the off-axis image response to fall off more rapidly than predicted by the classical cosine law, since it is reduced to near zero at angles larger than d/l (diameter/length). Nevertheless, we have used a copper and epoxy pinhole similar to the design shown in Fig. 3 to obtain images of 14-MeV neutron emission with a spatial resolution of 1 mm.⁵ We have found that a copper and epoxy design is more suitable for D + T neutrons whereas the polyethylene design is better for the lower energy D + D neutrons.

A simpler design results when the pinhole is replaced with an array of several detectors, each having long cylindrical collimating optics (Fig. 4). Such a device samples fewer points at the object plane but is more efficient because its entrance aperture is larger in area. We have recently assembled a collimated array of neutron spectrometers designed to measure the 2.5-MeV neutron yield along several chords through a plasma in the Laboratory's Mirror Fusion Test Facility (MFTF-B) device, scheduled for completion in 1985.

Our collimated MFTF-B spectrometer is distinctive both in its mechanical design and in the shield material used. Attenuation of 2.5-MeV neutrons generated by D + D fusion is greatest in

materials with the highest hydrogen density. Although polyethylene or paraffin are the materials of choice for the shield because of their high hydrogen content, they are difficult to mold in large pieces without shrinkage and cracking. In addition, neutron capture by hydrogen generates very penetrating 2.2-MeV gamma rays which can generate an undesirable background signal in the neutron detectors.

These problems were solved by using a shield material of polyethylene particles mixed with a small amount of boron carbide and bound in paraffin. (Boron strongly absorbs slow neutrons and greatly reduces the number captured by hydrogen.) The mixture is mechanically strong, relatively easy to cast in large pieces, does not contract or crack after casting, and generates significant gamma rays only at about 500 keV. Gamma rays of this energy are sufficiently attenuated by the polyethylene to minimize their intensity behind the shield.

The shield contains four entrance holes that accommodate any of several interchangeable apertures having a variety of collimation diameters. Each aperture can be independently aligned. We determine the axis of the collimator by reflecting a laser beam from a thin mirror placed in front of the detector onto fiducial markings inscribed on the experiment's vacuum vessel (see Fig. 4). Because fast neutrons readily penetrate the mirror, it may be left in front of the detector during an experiment. Each aperture moves freely within a well that is sealed against neutron radiation by a collar of oil, enabling easy realignment.

Fig. 4 Our collimated neutron spectrometer designed for the MFTF-B experiment (the detector assembly is not drawn to the same scale as the vacuum vessel and plasma). (a) The system consists of four liquid-hydrocarbon scintillation detectors shielded with a mixture of polyethylene particles and boron carbide bound in paraffin. Four entrance holes in the shield accommodate interchangeable apertures having a variety of collimation diameters. Each aperture is mounted in a sealed, oil-filled well to permit independent alignment. (b) To find the axis of a collimator, we reflect a laser beam from a thin mirror in front of the detector onto markings on the vacuum vessel of MFTF-B.

Figure 5 shows the spatial response of one of the collimating apertures measured using LLNL's Rotating Target Neutron Source I (RTNS-I). Because the field of view is ± 0.5 deg (full width half maximum), the plasma chord viewed from outside the vacuum vessel (6 m away) is only 10 cm in diameter. This gives a spatial resolution on the order of the Larmor radius of hot ions as they spiral about the magnetic field lines, which should prove to be adequate for experiments planned on MFTF-B. Resolutions of up to several Larmor radii will provide useful information. Although this instrument cannot be considered an imaging device, since it samples only a few points in the two-dimensional object plane, the sample points may be varied from shot to shot to generate a profile of the plasma.

Measuring Mean Ion Energy

The energies of neutrons generated by D + D and D + T fusion reactions depend on the initial energy of the reacting ions. (If the initial energy is essentially zero, the neutrons produced would be monoenergetic.) This dependence is the result of two distinct effects. The first and smaller effect is a direct transfer of kinetic energy from the reacting ions in the hot plasma to

the fusion-produced neutron. The second and larger effect results from the motion of the center of mass of the reacting ions relative to a fixed observer. The energy of a product neutron varies with its angle of emission relative to the motion of the center of mass of the reacting ion system as seen by the observer. For ions in thermal equilibrium, this angle is usually random, increasing the neutron's energy when it is emitted in the direction of the observer and decreasing it in the opposite direction. In consequence, the neutron energy spectrum seen by the observer is dispersed, a phenomenon called Doppler broadening. The Doppler width of the neutron spectrum is substantially larger than and increases with the mean ion energy of the plasma. For any isotropic Maxwellian plasma (that is, a plasma in thermal equilibrium), the Doppler width is given by

$$\Delta E_n = 67.4 \bar{E}_i^{1/2} \text{ (keV)}$$

for D + D neutrons, and

$$\Delta E_n = 144.5 \bar{E}_i^{1/2} \text{ (keV)}$$

for D + T neutrons, where $\bar{E}_i$ is the mean ion energy of the plasma, equal to $3/2$ of its temperature. These Doppler widths are much larger than those observed in atomic line radiation. Because of the large amount of energy released in the fusion reaction, the line widths are strongly amplified above the average energy of the plasma, a phenomenon that makes this type of measurement possible.

A High-Rate, Time-Resolved Neutron Spectrometer

The MFTF-B will provide a neutron yield more than adequate for time-resolved spectrum measurements. We have developed a neutron spectrometer system with sufficient energy resolution and high data-rate capability to observe the Doppler width in the neutron emission from MFTF-B plasmas, and its variation in time.^{6,7} The system, which will be located in the MFTF collimation assembly described earlier, uses liquid-

Fig. 5

To demonstrate the spatial resolution of the instrument, the collimated neutron spectrometer was swept past the RTNS-I line source of 2.5-MeV neutrons several times at different locations. The line source is obtained by viewing the edge of the RTNS-I target disk. The abscissa (θ) gives the angle between the source and the axis of the collimator. The data indicate that the collimated field of view was ± 0.5 deg (10 cm in diameter at the plasma) and that the out-of-field response fell to less than 0.1% of the on-axis response. Other scans indicate that the response falls off symmetrically on both sides of the peak.

hydrocarbon scintillation detectors similar to those used for neutron-yield measurements on TMX. A data unfolding program extracts the neutron energy spectrum from the observed energy distribution of the recoil protons.⁸

An important feature of the scintillator is that recoil protons generated by neutron interactions produce a slower fluorescence than do recoil electrons generated by gamma-ray or x-ray interactions. As a result, each type of radiation produces a characteristic pulse shape, enabling us to record simultaneously neutron and photon energy spectra in the same spectrometer.

We have developed a high-rate, time-resolved electronics system that analyzes the pulse height of scintillation-detector data and identifies the type of interaction at event rates up to 10 MHz, an improvement of two orders of magnitude over current data rates.⁸ Spectra are digitized with a resolution of 256 channels, readily upgradable to 512 channels. The system can record 50 neutron spectra per shot, the shortest accumulated over 50 to 100 ms. Spectra obtained during plasma build-up and decay can be reduced to Doppler width and mean ion energy after each shot. Data are reduced by a local microcomputer at a rate of about 10 s per spectrum. The system's neutron energy resolution remains adequate at the maximum data rate for making ion energy measurements in MFTF-B plasmas. Figure 6 shows a neutron spectrum unfolded from a 200-ms run at the RTNS-I.

Our data system is unique among nuclear spectroscopy instruments in providing digital control of all electronic adjustments. The local microcomputer sets all instrument parameters, which are recorded together with the data from each shot. In addition, digital control enables us to use fiber optics for data transmission, thereby isolating the system from the local environment (a requirement for high-power fusion experiments). The construction of this system is being funded by Princeton and will be implemented initially on their TFTR in 1983 to

Fig. 6

Neutron spectrum produced by D + D fusion, recorded with our high-data-rate spectrometer at the RTNS-I. The data were obtained in only 200 ms at a rate of 5 MHz. The energy resolution of the instrument was only slightly degraded at this high rate. The spectrometer will be used to make time-resolved neutron Doppler-width measurements on plasmas in the MFTF experiment, now under construction at LLNL.

measure neutrons generated by D + D and D + T reactions. We will be involved in bringing the system up at Princeton. Another such system will be used on the MFTF-B when that experiment is brought online.

Figure 7 shows some neutron energy spectra measured in the end-plug plasmas of the TMX with an early version of the MFTF-B spectrometer. The characteristic instrument line widths of the spectrometers varied from 160 to 200 keV at 2.5 MeV when unfolded from the experimental data. The spectrum on the west end-plug plasma showed a line width not significantly different from that of the instrument. The mean ion energy $\bar{E}_i$ had an upper bound of less than 4 keV, a value that agrees well with other types of plasma-energy measurements made on the same shots, including neutron yield.

The east end-plug neutron spectrum, however, showed a broad spectral line width that exceeded both that of the instrument and that observed on other shots when the plasma was known to be cool. Unfolding the instrument width from the data gave a Doppler broadening characteristic of a Maxwellian plasma with a mean ion energy of 14 to 17 keV. Because the TMX end-plug plasma is non-Maxwellian and anisotropic, with only about 5 to 7% of its ion energy in the axial direction, this value must be reduced slightly. The corrected energy is about 10 to 13 keV, in good agreement with other measurements.

Measurement of Doppler width enables us to determine directly the mean ion energy using a method that is independent of plasma density measurements. This is an important capability as the density profile of hot plasma is not always well known. The spectrometers are easily collimated, a feature

that enables us to use ion energy measurements to study the spatial profile of ion energy in various parts of the plasma.

Measuring Plasma Confinement and Heating

Neutron spectrum measurements also may be used to study the confinement time and slowing of particles in a plasma. Tritium is one of the reaction products of $D + D$ fusion (see Table 1). Some of the tritium is briefly confined in the plasma, so that $D + T$ fusion will occur even in a "pure" deuterium plasma. The relative rates of the two reactions provide important information about the confinement of charged reaction products such as tritium. Studies of $D + T$ fusion rates in deuterium plasmas also indicate how much charged reaction products slow before escaping the plasma. ($D + T$ reactivity is strongly peaked at about 100 keV, whereas the reaction product tritium is

Fig. 7

Neutron spectra measured on the east and west end plugs of the TMX, representing an accumulation of more than 30 shots. The spectral peak at 2.45 MeV results from $D + D$ fusion in the hot plasma. Energy dispersion in the neutron spectrum of the east plug is substantially larger than the resolution of the diagnostic instrument, indicating a

Doppler broadening characteristic of a Maxwellian plasma at a mean ion energy of 14 to 17 keV (corrected to 10 to 13 keV for the anisotropic TMX plasma). As energy dispersion in the west-plug neutron spectrum is not significantly greater than instrument resolution, any Doppler broadening is less than that due to 4-keV ion motion.

generated at about 1 MeV.) Such information is important in determining the extent to which reaction products provide supplemental heating.

Neutron spectrum measurements may also enable us to study energy deposition in a plasma by neutral beams. Energetic deuterium injected tangent to the plasma current in a tokamak-like device reacts with deuterium or tritium ions to produce neutrons whose energies are substantially shifted up or down by the beam energy, depending on whether the beam current is directed toward or away from the detector. If the injected deuterium is slowed significantly by the plasma before causing fusion, the energy shift is reduced. We have calculated spectral data for beam-target reactions to examine the feasibility of using neutron measurements to study the slowing processes that allow the beams to heat the plasma.

Impurities in a plasma, particularly those with a high atomic number (Z), scatter injected energetic ions away from the beam axis. When neutral deuterium is injected into a tokamak-like device tangent to the plasma current, beam scattering by impurities should cause observable changes in the beam-target neutron spectrum. (This effect results from the dependence, previously noted, of observed neutron energies on the angle between the detector and the motion of the center of mass of the ions.) Our computer simulations show that the energy resolution of existing spectrometers is adequate to measure the extent of pitch angle of scattering and thus to estimate the effective atomic number of the plasma, which indicates its impurity content.⁹

Summary

The improved magnetic confinement of hot plasmas is expected to result in substantial generation of fusion energy. As confinement improves, however, fewer energetic charged particles escape the central plasma, and diagnostic measurements must rely more heavily on uncharged reaction products (neutrons and gamma rays). We have developed neutron spectrometers with sufficient

energy resolution to measure the mean ion energy of magnetically confined plasmas at temperatures and densities characteristic of magnetic fusion experiments now and in the future. Such measurements may be highly resolved in time and space. Because spectrometer efficiency is absolutely calibrated, spectral measurements also implicitly contain fusion-rate data. Thus, it should be possible both to measure the fusion power of a machine and to study the buildup and decay of mean ion energy, the confinement of reaction products, the relative density of impurities, and the slowing of reaction products and of injected species. ■

Key Words: Doppler width; Magnetic Fusion Test Facility (MFTF); neutron spectroscopy; neutron imaging; thermonuclear fusion; Tandem Mirror Experiment (TMX).

Notes and References

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