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E-DIVISION ACTIVITIES REPORT

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E-Division Activities Report

July 1979

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. In addition this report describes work on accelerators, radiation damage, microwaves, and plasma diagnostics.

INTRODUCTION

E (Experimental Physics) Division carries out basic and applied research in atomic and nuclear physics as well as 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-17271-78) was issued in August, 1978. The report gives a brief review of the experimental 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.

LLL publishes monthly in the Energy and Technology Review (UCRL-5200) descriptions of programs of general interest. Last year's report (UCID 17271-78) included reprints of articles published in the Energy and Technology Review on the following subjects: Descriptions of the Electron Linear Accelerator, of the new intense 14-MeV neutron source (RTNS-II), and of the magnetic spectrometer used to study charged particles from reactions induced by 14-MeV neutrons; accounts of the "pulsed sphere" integral experiments and of determinations of the distribution of hydrogen isotopes in foils were included. The present report includes a reprint of an article on the use of models of the nucleus to predict neutron cross sections of interest to applications.

ACCELERATORS

Most of the activities of the division are centered around six accelerators: a 100-MeV electron linear accelerator (Linac), two 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 older of the two 400-kV accelerators ("ICT") produces 25 mA of atomic hydrogen, the newer one ("RTNS II") has produced 80 mA and should eventually reach the design current of 150 mA. A third 400-kV accelerator will become operational soon.

Although all the accelerators can serve as neutron sources most of the neutron experiments use either the Linac or the 400-kV accelerators. The Linac permits the simultaneous study of neutrons of energies from thermal to about 50 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.

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 a Ge-Li detector, 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.

Photon experiments are carried out at the Linac, which can produce monochromatic photon beams of variable energy. The photons arise from the annihilation-in-flight of positrons which have been accelerated in the Linac.

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

The tandem electrostatic accelerator, the cyclotron and the older 400-kV high current accelerator 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 1000 hours and in combination with the cyclotron for another 1000 hours. Beams produced were protons 80% of the time, deuterons 10%, and ^3He and ^4He the remainder of the time. The ICT accelerator operated for 1000 hours. The electron linac served as a neutron source for 2500 hours, as a γ -ray source for 1500 hours, and for other purposes 150 hours.

Intense Source of 14-MeV Neutrons

The national research facility containing an intense 14-MeV neutron source for fusion reactor materials research has begun operation. The Rotating Target Neutron Source project (RTNS-II) is an upgrade of the deuteron beam - rotating titanium - tritide target neutron source (RTNS-I) that has operated for over ten years. During the past year the first of

two neutron sources was completed. Tests of the accelerator began in September 1978 to check the efficiency of the beam transport system. In November 1978 production of 14-MeV neutrons started with a 23-cm diameter rotating tritium target. With this target a neutron source strength greater than 10^{13} per sec was achieved. Operation at higher source strength will be possible when larger-diameter targets become available. The second neutron source is still being assembled.

The experimental program has consisted of the following experiments: samples of 316 stainless steel from the Tokamak Fusion Test Reactor (TFTR) vacuum vessel have been irradiated. These will be later implanted with deuterium to investigate deuterium trapping at damage sites. Samples of Ag, Nb and Pt have been irradiated for later study by Transmission Electron Microscopy (TEM) which will investigate radiation damage cascade substructure. A composite sample was also irradiated. This contained pieces of the TFTR diagnostic window, samples of Nb, Ni and stainless steel and pieces of superconducting wire previously irradiated at the RTNS-I facility. These experiments will study the effect of higher neutron fluences on the diagnostic windows, the mechanical properties of metals for comparison to light ion induced damage and the critical point of superconductors.

EXPERIMENTAL NUCLEAR PHYSICS

Fission

The nuclides ^{245}Cm and $^{242}\text{Am}^{\text{m}}$ are two of the major transplutonic elements of concern to such applied problems as actinide burn-up and ^{252}Cf production. Important parameters for determining the reactivity of these fissionable materials are their fission cross sections and the average numbers of neutrons per fission ($\bar{\nu}$). The fission cross sections of ^{245}Cm and $^{242}\text{Am}^{\text{m}}$ have been measured simultaneously relative to ^{235}U using a 195 μg sample of $^{242}\text{Am}^{\text{m}}$ and a 380 μg sample of ^{245}Cm . The purity of both samples was greater than 99%. The fission cross sections were measured between neutron energies of 10^{-4} eV and 20 MeV with an uncertainty of $\pm 5\%$ between 1 and 5 MeV and somewhat higher uncertainty at higher neutron energies. For ^{245}Cm the average number of neutrons per fission was measured from 100 keV to 30 MeV relative to $\bar{\nu}$ for ^{235}U with an uncertainty of $\pm 5\%$ at 1 MeV and $\pm 25\%$ at 15 MeV.

The number of neutrons per fission was also measured for ^{232}Th relative to ^{235}U in order to investigate whether $\bar{\nu}$ shows any unusual behavior near the fission threshold and near the threshold for second-chance fission, i.e., at the energy where fission can take place after a neutron is emitted by the compound nucleus. The measurements extended from the fission threshold to 30 MeV and had an uncertainty of about 4%. No unusual effects were observed.

There has recently been a heightened awareness that current knowledge of the spectrum of prompt neutrons from fission is poor. There are uncertainties in both the high- and low-energy ends of the spectrum. Calculations of the spectrum have usually not included details of the properties

of the fragments that emit the neutrons. A new statistical (Hauser-Feshbach) calculation of the neutron spectrum from spontaneous fission of ^{252}Cf is based on the assumption that the neutrons are emitted from the fragments after fission and uses information on the excitation energies of individual fragments. The calculated spectrum has the same shape as the data above 3 MeV, but at the lower energies deviates from the data. The discrepancies at low energies suggest either that the measurements are in error, or that another mechanism for neutron emission is important, such as emission before the fission fragments are fully accelerated by their mutual repulsion.

Neutron Cross Sections

Hydrogen and helium are produced by nuclear transmutations by fast neutrons. These gases will produce radiation damage in future fusion reactors. In a collaboration with the University of Wisconsin, cross sections for the emission of protons, deuterons, and alpha particles have been measured for 15-MeV neutrons interacting with the major elemental and isotopic components of stainless steel. Measured angular distributions of the emitted charged particles provided information about the relative importance of compound nucleus and preequilibrium processes. Further measurements on ^{11}B , C, ^{89}Y , ^{90}Zr , and $^{92,94,95,96}\text{Mo}$ are still in the process of evaluation. The data on these materials together with the already completed studies form an extensive basis for checking nuclear reaction models and for direct use in improving nuclear data evaluations for applied purposes. Technical advances in the past year have included measuring alpha particles below 1 MeV with a three-counter coincidence detector. A two-dimensional computer-based analyzer has facilitated data collection and particle identification.

In order to extend the useful energy range of the Linac to 60 MeV neutron energy a new target for producing neutrons has been developed. This target consists of tantalum and beryllium and has increased the neutron intensity above 20 MeV by a factor of four. In addition the detection efficiency for the most energetic neutrons has been greatly increased by use of a new system consisting of 16 independent scintillators, each viewed by two photomultipliers. With this system the total neutron cross sections of ^{140}Ce , ^{142}Ce and ^{141}Pr have been measured from 3 to 60 MeV. The absolute values of the cross sections were measured to 1 - 3% while the ratio of the cross sections of ^{140}Ce and ^{142}Ce was determined to 0.3%. Knowledge of the difference between the cross sections of the two isotopes should yield information about the magnitude and energy dependence of the symmetry term in the optical potential describing the neutron-nucleus interaction.

Neutron Cross Sections Deduced from Proton Experiments

Because of the experimental difficulty of performing accurate neutron experiments, the charge-exchange reaction is useful for obtaining neutron-nucleus potentials. This model assumes a simple charge-exchange force which converts a proton incident upon a nucleus to a neutron. Because the residual nucleus is left in a configuration called the analog state closely related to the target nucleus, it is possible, in principle, to determine the neutron potential for the target nucleus. In earlier work with protons incident on ^{119}Sn the neutron potential deduced from the experiments agreed with available neutron data considerably better than did some widely-used neutron potentials. For Mo isotopes, however, neutron potentials extracted from accurate neutron elastic scattering data had a different energy dependence from that of the potentials extracted from the (p,n) measurements.

In order to understand this lack of agreement, which speaks against the simple charge-exchange model, charge-exchange cross sections were measured for ^{62}Ni and ^{64}Zn from 12 to 26 MeV, corresponding to neutron energies of 2.5 to 16.5 MeV. Excitation functions of the angle-integrated cross sections exhibited a strong energy dependence for both isotopes. Attempts to force the model calculations to fit this energy dependence by varying the neutron potential were successful only if the fit to the angular distributions was allowed to deteriorate markedly. More complicated calculations using a microscopic formulation with exchange and an effective nucleon-nucleon interaction were also unsuccessful. Apparently some more complicated mechanism is interfering with the direct charge-exchange process in this energy range.

Another approach to determinations of elastic and inelastic neutron scattering is to measure elastic and inelastic proton scattering cross sections at corresponding bombarding energies. Neutron energies around 15 MeV are of particular interest to applications. For the transuranic elements the corresponding proton energies are between 20 and 35 MeV. Elastic and inelastic proton differential cross sections were measured for ^{232}Th and ^{238}U using 20- and 26-MeV protons from the cyclograaff and the Enge split-pole spectrometer detection system. Proton groups corresponding to states up to the 8^+ level in the ground state rotational band have been measured. The analysis of the data is in progress with the aim of extracting values for the deformation parameters β_2 , β_4 , and β_6 . The proton measurements allow deduction of neutron cross sections and give information on the deformation parameters and their energy dependence.

Proton inelastic scattering measurements were completed for the Eu isotopes 151, 152, 153, and 154. Both ^{152}Eu and ^{154}Eu are radioactive. Earlier work showed that the transition from a spherical nucleus to one which is strongly deformed occurs at ^{152}Eu . The measurements on ^{154}Eu give nearly the same deformation as ^{152}Eu . A comparison of the two measurements suggests that both nuclei have the same ground state configuration.

A third approach to deducing neutron cross sections from proton cross sections involves the use of the inverse reaction. Weapons test diagnostics use threshold (n, 2n) detectors, such as ^{89}Y . At high neutron flux density, destruction of the (n,2n) product ^{88}Y becomes significant, so that the total destruction cross section must be known in order to extract reliable information from the threshold detector. Part of the destruction cross section is from (n,p) reactions. This cross section for unstable ^{88}Y may be deduced from the inverse reaction $^{88}\text{Sr}(p,n)^{88}\text{Y}$. Complete angular distributions to the ^{88}Y ground state and two excited states were obtained in 0.25 MeV steps between 5.75 and 10 MeV, and at 11, 12 and 16 MeV. Between 7 and 16 MeV bombarding energy the neutron evaporation spectrum was also obtained in order to yield information on the ^{88}Y level density.

Because of the importance of (n, α) reactions to the assessment of radiation damage an effort is underway to measure (p, α) cross sections and to develop a theoretical model that fits the (p, α) results and that can be used to predict (n, α) cross sections. The angular distributions of α particles emitted when 26-MeV protons bombard ^{89}Y and ^{209}Bi have been measured. The theoretical model takes into account the precompound mechanism of alpha particle emission, and describes this mechanism by an exciton model and quasifree scattering.

Neutron and Proton Radiative Capture

For calculations of radiative-capture cross sections for which no measurements are available, a compound-nucleus "Hauser-Feshbach" model has been used in the past. This model is inadequate for neutrons of energy above a few MeV where other reaction mechanisms become important. Another model ("direct-semidirect") has been employed at the higher energies, but it has not been successful in fitting all the data with consistent parameters. A new method ("pure-resonance") has been applied with reasonable success to both proton and neutron capture in ^{208}Pb . Both fast-nucleon capture models are based on the same physical processes, and the improved results with the new model appear to be due to a better treatment of the way in which the projectile excites the giant-dipole resonance, which dominates the reaction.

This new model has also been applied to carbon. Angular distribution measurements of neutrons from γ rays on ^{13}C (performed at Toronto) had shown anomalous backward peaking of the neutrons at excitation energies between 14 and 18 MeV. This is probably due to electric quadrupole radiation and could not be fitted by the direct-semidirect model. The problem was further investigated by measurements of the angular distributions of capture γ rays from $^{12}\text{C}(p,\gamma)^{13}\text{C}$. The γ rays were detected in the large NaI spectrometer. Calculations are in progress to compare the results of the measurements with the predictions of both the direct-semidirect and the pure resonance models.

For measurements on nuclear explosions using radiochemical methods a knowledge of the neutron capture cross sections of unstable nuclides is needed. The mass region around $A = 90$ is of particular importance.

An important parameter in calculations of the cross sections is the γ -ray strength function. To obtain information on this quantity, the shape of the neutron-capture γ -ray spectrum has been measured using a 3 crystal Ge(Li) spectrometer for the reaction $^{87}\text{Sr}(n,\gamma)$ for several neutron energy regions between 1 eV and 100 keV, as well as for the 3.5-eV resonance. This measured spectral shape can be compared directly with calculations of the spectral shape assuming various γ -ray strength functions. The parameters can then be used to calculate neutron capture cross sections on ^{87}Sr in the same energy regions.

Another effort to determine γ -ray strength functions involves measurements of γ -ray spectra from proton radiative capture. The measurements were made with a large NaI spectrometer and with lithium-drifted germanium detectors. The targets were natural Rb, ^{88}Sr , ^{89}Y , ^{90}Zr , ^{92}Mo , ^{96}Mo , and ^{100}Mo . Fitting the energy dependence of the gamma spectra requires significant modifications of the prescription for gamma-ray strength functions that has been most commonly used in statistical-model calculations.

Photonuclear Reactions

Monoenergetic photons from positron annihilation in flight were used to measure the $^3\text{H}(\gamma,n)^2\text{H}$, the $^3\text{H}(\gamma,2n)^1\text{H}$, and the $^3\text{He}(\gamma,n)2\text{p}$ cross sections from threshold to 32 MeV with a photon energy resolution of 200 to 400 keV. Both the ^3H and ^3He samples were gases at high pressure (up to 300 atm) in cylindrical steel tubes. The neutrons were counted in boron detectors embedded in paraffin. The results of the measurements agreed well with calculations that take into account final state interactions.

The total photoneutron cross section of ^{17}O was measured in the region of the giant resonance between 20 and 26 MeV. The results are compared with the differential ground-state cross section for ^{17}O . The total cross section contains both isospin $T = 1/2$ and $T = 3/2$ components, whereas the ground-state result must have only $T = 1/2$ strength.

The angular distributions of neutrons emitted by ^{16}O when excited by photons in the energy range from 25 to 45 MeV were measured with bremsstrahlung photons. The neutron energy was measured by time of flight along six separate 10-meter flight paths. The angular distributions are sensitive to the quantum properties of the nuclear levels being excited. In this energy range the strongest transitions are electric dipole. By measuring the angular distribution, a small admixture of electric quadrupole strength was detected. The measurements place lower and upper limits on the electric quadrupole strength in this energy region. These limits indicate the existence of a quadrupole giant resonance predicted by theoretical models.

Interactions of Light Nuclei

Interactions between light nuclei have been successfully described in a parameter-free way by the resonating-group method. This method, based on a variational principle, is fully-antisymmetrized and uses an experimentally determined nucleon-nucleon interaction, including exchange and spin-orbit terms. Elastic scattering and bound states of the two light clusters are described well by this method, but, unless coupled-channel calculations are used, reactions are described in terms of a phenomenological imaginary potential. Verification of this potential has been difficult or impossible in many cases because of a lack of total reaction cross section measurements. Using a method that relies on the symmetry about 90° in the center-of-mass system for identical particles, the total reaction cross

section for $^3\text{He} + ^3\text{He}$ was determined at energies of 17.9, 21.7 and 24 MeV using the LASL tandem accelerator. The measurements also yielded cross sections for the production of protons, deuterons, tritons, ^3He , and alpha particles.

Integral Experiments

The neutron and γ -ray transport and resulting effects in large systems are usually calculated from microscopic cross sections. Because of the variety and large number of cross sections that are often required, integral experiments are of great importance to check the validity of the cross sections used in the calculations. Such experiments can also reveal errors in the computer codes.

A type of integral experiment that was developed for this purpose is the pulsed-sphere experiment in which a pulse of 14-MeV neutrons is produced at the center of a sphere of the material to be studied. The emerging neutrons are detected in a stilbene scintillator. The results of measurements on Cu, Nb, Th, and ^{238}U were previously compared with calculations based on the widely used ENDF/B-IV file of evaluated cross sections. Large discrepancies between calculations and experiments in the neutron energy region between 5 and 10 MeV are due to an insufficient number of energetic secondary neutrons in the evaluations. The recently published version V of the ENDF/B file for Au, Th and U yields much better agreement for Th, but for Cu and ^{238}U the disagreement is at least as bad as for version IV.

In a collaborative effort with Los Alamos the low-energy neutron emission spectra from ^6LiD spheres bombarded with 14-MeV neutrons were measured with a ^6Li glass detector. These data supplement previous high-energy spectra measurements taken with a stilbene detector by extending the previous measurements which cut off at ~ 1 MeV down to ~ 10 keV. The neutron spectra measurements complement the direct tritium production measurements carried out at

Los Alamos for a 600-mm ^6LiD sphere bombarded at its center with 14-MeV neutrons. Good agreement was obtained between measurements and calculations for the tritium production and for the emission spectra between 14 MeV and ~ 27 keV, but there are discrepancies below 27 keV.

Effects of residual radiations are of interest to the weapons program. Integral experiments have been performed to test calculations based on a compilation of activation cross sections. In these experiments, a desired neutron spectrum is produced by surrounding a 14-MeV neutron source with moderating materials in a spherical geometry. Small samples of the materials of interest are irradiated in this neutron spectrum. The γ -ray spectra and half-lives of the activated samples are measured in a lithium drifted germanium spectrometer. In the past, these measurements have shown errors both in some of the cross sections and in some of the calculational procedures. Experiments during the last year have aimed at improving the accuracy of the measurements. Specifically, an experiment has been done with samples of Y, Zr, Au, and Th that is expected to yield relative accuracies of better than 5% and an absolute accuracy of about 10%.

THEORETICAL NUCLEAR PHYSICS

Nuclear Deexcitation at High Angular Momenta

Model calculations have been made for deexcitation of 'superdeformed' nuclei predicted to be formed in heavy ion reactions. Superdeformed nuclei are prolate nuclei predicted by the rotating liquid drop model which have major axes as much as twice those of the spherical nuclei of the same volume.

A Hauser-Feshbach code has been modified to use a set of transmission coefficients which are calculated as a function of angular momentum and deformation. This has been applied to the system $^{40}\text{Ar} + ^{109}\text{Ag}$, for which many experimental data exist. When transmission coefficients of deformed rather than spherical nuclei were used, gamma decay rates increased by a factor of a hundred. This altered the predicted deexcitation from being all fission to alpha decay followed largely by light particle emission. Residual nucleus angular momenta tended to become constant as compound nucleus angular momenta continued to increase. The theoretical predictions of this deexcitation mechanism generally agree with and explain experimental observations.

Nuclear-Coulomb Interference Effects in Proton Inelastic Scattering in the Actinide Region

Coupled-channel calculations using a Coulomb potential derived from a deformed homogeneous charge distribution often fail to reproduce the measured angular distributions from deuterons inelastically scattered from the first 2^+ state in ^{238}U . However, the introduction of a diffuse charge distribution for both the target and projectile provides good agreement with the experimental results. A comparison between recent

measurements of the inelastic proton angular distributions from ^{232}Th and ^{238}U at 20 and 26 MeV and calculations carried out with a coupled-channel code has shown discrepancies similar to those observed for deuterons. In order to improve the calculations the code has been augmented to allow for a more realistic calculation of the Coulomb interaction potential. The original version assumed a uniform charge distribution within the Coulomb radius; the new version allows for the choice of a uniform or a Fermi distribution with an adjustable width parameter. Another change of the code permits a more accurate representation of the radial dependence of the potential in deformed nuclei. In addition to the Taylor expansion of the nuclear radii, a Legendre expansion is included. Calculations are in progress to test the improvements in the code with these modifications.

ATOMIC PHYSICS

The principal activity in atomic physics has been the study of atomic inner-shell vacancies in ion-atom collisions. The molecular model provides a convenient framework for understanding inner-shell vacancies produced in collisions of low-velocity heavy ions with atoms. With this model many experimental results can be interpreted in terms of a transfer of electrons from one molecular state to another during the collision. The best calculations involve solving complicated differential equations. The solutions can sometimes be simplified by assuming that the coupling takes place between two states and using an analytical expression for the energy gap of the two states that couple. Many analytical solutions have been published but the results often differ widely. This problem is investigated by examining the sharing of inner-shell vacancies between two collision partners. The sharing results when a vacancy, which has been produced at some smaller internuclear distance, is transferred from one molecular orbital to another during the separation of the collision partners. By using collision partners with different atomic numbers the character of the "level crossings" can be changed. Two types of level crossing have been studied: In one the molecular levels repel, in the other they attract one another. Experiments are being performed to test the limits of theories that have been proposed to explain these data.

POSITRONS

Material Science

One of the most difficult problems in the design of a fusion reactor is the short lifetime of the wall of the plasma-containing vessel caused by radiation damage induced by 14-MeV neutrons. The selection of a suitable material requires a better understanding of the factors that influence the behavior of materials under bombardment by 14-MeV neutrons. Because of the low intensity of available 14-MeV neutron sources, other high-energy neutron sources are often used in radiation damage studies, or protons or other charged particles serve to simulate the effects of neutrons. In experiments using either neutrons or protons, radiation damage is detected by measuring the lifetime of positrons introduced in the damaged area.

The similarity between proton and neutron induced radiation damage has been demonstrated in both copper and silver irradiated at room temperature, especially in silver by comparing trapping rates as a function of dose for protons and neutrons. The effect of a threshold in the secondary recoil spectrum which was previously found in copper was also observed in silver. An observed effect of impurities on void formation in irradiated copper at room temperature remains unexplained.

Amorphous metallic systems (glassy metals) have been studied by positron lifetime analysis after deformation or embrittlement, and by electron microscopy after implantation of seven atomic percent of helium. No microscopic effects have been observed caused either by deformation, He implantation or by embrittling the amorphous material even though there are changes in macroscopic characteristics.

Radiation from Channeled Positrons

In a collaboration with Stanford and ORNL, we observed channeling radiation caused by the trapped motion of 56-MeV positrons in the crystal planes of Si. The work was based on theoretical predictions worked out at Stanford and on earlier experiments on positron and electron channeling in thin single Si crystals performed at LLL. The present results show the expected peak in the radiation spectrum observed with a Ge detector at energies of 35 to 45 keV in trapping along the (110), (111), and (100) planes. The predicted peak energies are given by $E_Y = K E_e^{3/2} E_0$, where K is a known constant, E_e is the positron energy, and E_0 is the interplanar energy parameter (2 eV). This agrees to about 10% with estimates based on crystal models for the ion potentials between major crystallographic planes.

DEVELOPMENT PROJECTS

High Power Microwaves

High-intensity electromagnetic fields in the microwave frequency range are useful for heating plasmas, for generating intense charged-particle beams, and other applications. A method is under development for filling a superconducting resonant cavity with rf energy for a relatively long time and then extracting the energy during a much shorter time to achieve a power gain of the order of $10^6 - 10^8$. This would make power levels of many TW possible.

A thin-walled, spherical, superconducting resonant 1.5-liter cavity has been used to accumulate approximately 0.25 J of electromagnetic energy at 8.14 GHz. The energy has been extracted in a pulse of about 2- μ s duration, with a peak power of 150 kW. In the initial high-power experiments the cavity of lead-plated copper had a Q-value of 5×10^7 , and the power gain was forty (input power was provided by a klystron operating at 4 kW). Such cavities can operate at Q values two orders of magnitude higher and should be able to produce power gains of several thousand. Niobium cavities of the same size and configuration are now under construction; with these cavities power gains on the order of 10^5 should be achievable, with peak output levels in the MW range. The work is being carried out in collaboration with physicists from the Research Advisory Institute who developed the fast switch that serves to extract the energy from the cavities. The goal is to develop larger cavities capable of storing 100 kJ.

Dense Plasma Focus

The Dense Plasma Focus project which is based in T-Division involves measurements and technical support in E-Division. The aim has been to investigate whether enough energy can be concentrated in a short time on a small target to produce thermonuclear reactions. The targets have been small spheres filled with a DT mixture, but so far no thermonuclear neutrons have been produced.

The present aim is to study the efficiency of energy coupling between the plasma focus discharge and low mass targets, such as 10- μ m fibers of glass and plastic, bundles of glass fibers, and aluminum ribbons, and to deposit a few hundred joules in targets of mass between 10^{-5} and 10^{-4} g in approximately 10 ns. Target temperatures of 100 eV have been observed.

Space Charge Lens

A space charge lens consists of a cylindrical electron trap produced with ring electrodes in an axial magnetic field. The electric field within the trapped electron cloud is radial, increases with radius, and is responsible for focusing positive ions. Such lenses are useful for focusing high-current light or heavy ion beams, and hold promise for precision ion-optical applications.

A number of electrode geometries have been studied in a cooperative project with the University of Oregon. One lens mounted near the extractor of a duoplasmatron ion source has delivered 175 mA of 30-keV H^+ ions through an analyzing magnet for six hours. Another produced a focal spot of 0.2-mm diameter when a 1-cm diameter beam of 1.2-MeV protons was focused 90 cm from the lens.

Shielding Design

A knowledge of the yield and spectrum of neutrons and photons produced in the bombardment of thick targets is necessary for the design of shielding for accelerators and for military applications. Such yields and spectra were measured for 220 MeV protons and 330 MeV deuterons produced in the LBL Bevatron, incident on thick targets of various atomic numbers. For each target, neutron energy spectra and prompt γ -ray yields were measured using the time-of-flight technique. The neutron yields and the prompt γ -ray yields were found to depend on the atomic number of the target and on the incident projectile, while the shape of the neutron spectra remained the same.

Neutron Diagnostics for Fusion Experiments

Measurement of important plasma parameters in thermonuclear fusion experiments is becoming increasingly difficult because of larger plasma volumes and higher ion densities. Some of the diagnostic methods used successfully in earlier experiments are no longer useful because of signal attenuation in the plasma. Neutron attenuation in the plasma is negligible, however, and recent experiments produce neutrons from $D(d,n)$ and $T(d,n)$ reactions at rates up to 10^{19} n/sec for 50-500 ms. A study is being carried out with groups at Princeton and MIT to apply neutron measurements to the determination of plasma parameters.

Calculated $D(d,n)$ and $T(d,n)$ neutron spectra and experimental spectrometer lineshapes showed that the effective nuclear charge of impurities (Z_{eff}) may be determined from neutron spectra during neutral beam heating of a toroidal plasma. In addition, the spatial distribution of Z_{eff} and of the ion temperature may be determined. Available energy resolution is

marginally adequate at the temperatures of interest, but improvements by a factor of 2-5 may increase the reliability of the proposed measurements.

Systems are being installed on the endplugs of the LLL Tandem Mirror Experiment for evaluation. Gas scintillation counters containing Ne or $^3\text{He} + \text{Xe}$ gas are being studied as possible spectrometers for measurements during the ~ 10 -ms times characteristic of ion fluctuations.

LUNG FUNCTION EFFECTS OF OZONE

In a cooperative program with the Department of Environmental Health and Community Medicine at the University of Washington functional changes in the lungs caused by low ozone concentrations are studied. The experiments use radioactive nitrogen produced at the Linac as tracers to measure changes in ventilation and clearance rates. Positrons from ^{13}N decay are detected with an Anger camera. Conventional tests measure flow resistance, dynamic compliance, and multiple-breath nitrogen washout, while the radioisotope technique determines regional and overall nitrogen wash-in.

Each dog was measured twice before and twice during the three-hour ozone exposure. Dogs are grouped according to ozone concentrations of 0.12, 0.22 and 0.45 ppm. The animals were anaesthetized and mechanically ventilated. Changes in the local distribution of ventilation followed exposure to ozone. Conventional tests of overall function of the lung were unaffected. These findings indicate slight changes in diameter of small peripheral airways. The relation of this functional response to the long-term health of the lung is uncertain. Impairment of ventilation occurred at a concentration as low as 0.13 ppm. This is almost the same concentration as the new standard for ozone of 0.12 ppm (one hour average) proposed earlier this year; the original standard had been 0.08 ppm.

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Nuclear modeling at the LLL Cyclograaff

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The design of nuclear devices, from fusion and fission reactors to nuclear weapons, requires a reliable nuclear data base. Often we need to know about reactions and nuclear species that cannot be measured directly. In addition, we may require some knowledge of cross sections for materials that are difficult or impossible to obtain in sufficient quantity for experimental study. Nuclear modeling, a synthesis of theory and experiment, provides a way of supplying the needed information. For the various models to be credible, their predictions must be verified over as wide a range of nuclear masses and particle energies as possible. At LLL we are supplying this verification through an experimental program tailored to the relevant models as well as to the particular applications.

Fission and fusion reactors and nuclear explosions create radioactive nuclides by various nuclear interactions, of which neutron-induced reactions are most interesting. If the half-lives of these unstable nuclides are long enough, the unstable nuclides may undergo further interactions with the neutron flux. These second-order interactions in turn may affect device performance by transmutations, or they may influence diagnostic reactions. The production of helium in fission reactors by the two-step reaction on nickel is a classic case of an important second-order reaction [$^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}$ and $^{59}\text{Ni}(n,\alpha)^{56}\text{Fe}$]. Because of the instability of the intermediate nuclei in question, the cross sections for the second step are often not measurable, with the result that cross-section-dependent uncertainties are introduced into the design calculations and analyses.

In the absence of credible direct measurements, modeling is the best way to obtain the needed information. Even for some cases

where direct measurements are possible, nuclear modeling may still be the most cost-effective means to obtain the required data.

Problems associated with the instability of the nucleus also arise in the investigation of certain materials. For example, the nuclide $^{242\text{m}}\text{Am}$ is produced in fission reactors. To understand its destruction, one needs to know both the fission and the neutron-capture cross sections. Because of the large gamma-ray background from a $^{242\text{m}}\text{Am}$ decay product, the capture cross section cannot be measured with present laboratory techniques. Although some of these reactions may be studied using the intense neutron flux from a nuclear explosion, this technique is expensive and lacks the reproducibility and accuracy of a good laboratory experiment.

Modeling: the synthesis of theory and experiment

For stable or long-lived target materials, the determination of a nuclear cross section for a particular reaction is straightforward in principle. Typically, a beam of particles produced by an accelerator bombards an appropriate target material, and the subsequent reaction products are detected. In this way cross sections for the interaction of neutrons, photons, and various charged particles are measured routinely at LLL with our accelerator facilities. These measurements may be combined with nuclear models to determine cross sections for unstable materials of importance in applications.

Figure 1 illustrates how we attempt to derive specific nuclear data when a direct measurement is not feasible. The data are derived by a combination of indirect measurement (where something closely related to the desired reaction is measured), theoretical prediction, experimental verification of the theories, and subsequent code refinement. We refer to this entire series of procedures as nuclear modeling.

With nuclear models, we can predict scattering and reaction cross sections and spectra of emitted radiation and can extrapolate

from direct measurements to regions where no measurements exist. For each model, our indirect measurements together with selected verifying experiments give us a good estimate of the reliability of these extrapolations.

Although many details are known about the force acting between an isolated pair of nucleons, the many-body nature of the problem and the complex nature of the force make it impossible to calculate from first principles the interaction between two nuclei. Instead, we must rely on a variety of

different phenomenological models that reflect different facets of the problem; these models may be classified as either static or dynamic. In the static case, we are concerned with the properties of a noninteracting nucleus; in the dynamic case, we are concerned with the possible modes of interaction of a nucleus with a particle, a photon, or perhaps another nucleus. In determining cross sections, the static property data are indispensable ingredients for the dynamic calculations.

Figure 2 illustrates some of the

different models that are important for our nuclear modeling program. We have tried to classify these models according to different limits: static vs dynamic, single-particle vs many-particle, single-interaction vs many-interaction. In practice, however, the boundaries become blurred, and we must know enough about the unstable nucleus to choose the model or technique for a given problem and to predict its accuracy. One of our principal efforts is a broad program of experimental verification and testing of the accuracy and limits of

applicability of the various models. As a result, we have resolved specific problems and have introduced a number of refinements for predicting nuclear cross sections reliably.

Illustration of nuclear modeling

Determining cross sections on unstable nuclides. Capture of neutrons by unstable nuclei affords a good example of our nuclear modeling. Consider the short-lived nuclide ^{89}Zr , which is formed by the $^{90}\text{Zr}(n, 2n)$ reaction. When ^{89}Zr

captures a neutron, it again becomes ^{90}Zr (Fig. 3). In the capture process, the ^{90}Zr is formed in an excited state (the compound nucleus), and its excess energy may be emitted as a cascade of gamma rays—this is the (n, γ) reaction. To calculate the (n, γ) cross section, we must know the details of the neutron absorption and the subsequent gamma-decay process. In addition, we must have other information about the compound nucleus, such as the density of its nuclear energy levels and competing modes of decay. Means for

calculating the neutron absorption are understood reasonably well, but the theory of the gamma decay of the compound nucleus is very uncertain and requires a long extrapolation from regions where measurements exist. The resulting calculated (n, γ) cross sections are, therefore, very uncertain.

Our approach is to supply the answer to part of the problem by a closely related laboratory measurement. When stable ^{89}Y is bombarded with protons, the same compound nucleus ^{90}Zr is formed. The compound nuclear model, which applies in this problem, tells us that the decay of ^{90}Zr is independent of its manner of formation. Consequently, such a measurement provides directly the gamma-decay information needed to make the (n, γ) cross-section calculation. Furthermore, by comparing this information with current theories, we can study their usefulness and adapt them to cases such as ^{88}Zr where the (p, γ) technique is not applicable because ^{88}Y is also unstable.

Using the tandem Van de Graaff facility and our large sodium-iodide gamma spectrometer, we have completed (p, γ) measurements on ^{90}Zr , ^{89}Y , and ^{88}Sr . We use the data to deduce neutron-capture cross sections for the unstable nuclei ^{90}Nb , ^{89}Zr , and ^{88}Y . We have also made similar measurements on molybdenum isotopes of similar mass— ^{92}Mo , ^{96}Mo , and ^{100}Mo —to

test our ability to calculate the gamma-decay branch. Some results for ^{88}Sr are shown in Fig. 4, where the total energy released as gamma rays is plotted as a function of proton bombarding energy—a quantity closely related to the neutron-capture cross section. The black curve represents our present ability to model this reaction, and its good agreement with measurements indicates that reasonably accurate predictions of the neutron-capture cross sections can be made.

To be sure of our ability to predict (n, γ) cross sections from

(p, γ) measurements on a neighboring nuclide with the same mass number (such as ^{89}Y relative to ^{89}Zr), we are performing a test in which both cross sections can be measured. In this experiment, the 100-MeV electron linear accelerator¹ will be used as the source of neutrons for measuring neutron capture on stable ^{87}Sr ; the proton measurement on long-lived ^{87}Rb will again be done at the tandem Van de Graaff facility. Both of these measurements will investigate the production of ^{88}Sr . The results of this specific comparison will be available later this year.

LLL Cyclograaff facility

Experimental measurements to support nuclear modeling require a wide variety of incident beams and a comparably versatile set of detectors for the reaction products. In the above example, proton beams were required, and the reaction products detected were gamma rays. For other, confirmatory reactions such as $^{87}\text{Sr}(^3\text{He}, \gamma)$, $^{87}\text{Sr}(^3\text{He}, n)$, and $^{86}\text{Sr}(\alpha, n)$, beams of ^3He and alpha particles are required. Similarly, beams of deuterons and of heavier projectiles such as ^6Li and ^7Li are also often useful. Our Cyclograaff facility

provides these beams over the ranges of energies most useful for nuclear modeling for applied nuclear data.

The LLL Cyclograaff facility (Fig. 5) is based on two accelerators that can be used individually or in series. The 71-cm negative-ion cyclotron produces beams of H^- or D^- ions. The tandem Van de Graaff (Model EN) can accept the beams from the cyclotron and accelerate them further. Or it can be used alone to produce beams of protons, deuterons, ^3He , and alpha particles, as well as heavier ions, including lithium, carbon, oxygen,

fluorine, and bromine. The beams and their energy ranges are given in Table 1. In addition, these beams can be used with suitable targets to produce monoenergetic neutrons. Typically, the $^3\text{H}(p, n)^3\text{He}$, $^2\text{H}(d, n)^3\text{He}$, and $^3\text{H}(d, n)^4\text{He}$ reactions are used as the source reactions.

Each of these beams can be pulsed for time-of-flight experiments where we measure the time between the nuclear reaction and the arrival of the resultant radiation at the detector. These experiments are particularly useful for determining the energy of neutrons, a

Fig. 5 The LLL Cyclograaff Facility. Beams of charged particles are accelerated by the negative-ion cyclotron and the EN tandem Van de Graaff accelerator. These beams interact with target nuclei at the

indicated experimental stations where there are detectors for the reaction products, which include gamma rays, neutrons, and charged particles.

quantity best determined from their velocity.

The experimental apparatus for studying the reaction products includes detectors for neutrons, gamma rays, and charged particles. A unique 16-detector array for neutrons (Fig. 5) is used to measure the angular variation of emitted neutrons. A heavily shielded gamma-ray detector [NaI(Tl) 25 cm long by 25 cm in diameter] detects energetic gamma rays with good efficiency. Germanium detectors are used for high-resolution studies of gamma rays. Charged-particle reaction products are detected by conventional silicon surface-barrier detectors or, for better resolution, by an Enge split-pole magnetic spectrometer (Fig. 5).

Applications of nuclear modeling

Neutron transport. The above example uses models listed in Fig. 2: the unified model as the nuclear

structure model and the compound-nucleus model as the dynamic or reaction model. Other models are valuable for other applications. In the realm of direct-interaction nuclear dynamics (see Fig. 2), the optical and nuclear collective models are used to calculate neutron elastic and inelastic scattering. Here again, we may check the validity of these

models using specialized techniques.

The so-called (p,n) charge-exchange reaction allows us to infer neutron-scattering cross sections from the experimentally simpler proton scattering, which also requires far less material for a measurement. The specificity of the charge-exchange reaction mechanism for medium and heavy

Table 1 Beams from the LLL Cyclograff.	
	Energy, MeV
Particle	
Protons	0.1-12, 15-27
Deuterons	0.1-20
^3He or ^4He	0.1-18
^6Li or ^7Li	0.1-24
C	0.1-42
O	0.1-48
F, Cl, Br	0.1-50
Secondary radiation	
Neutrons	0-35

Fig. 6 Angular distribution of neutrons elastically scattered from natural tin and antimony. The curves are model predictions based on systematics of proton scattering data, measured (p,n) charge-exchange cross sections, and application of a particular direct-interaction nuclear model.

nuclei was discovered at LLL in 1961 and has been used as a routine tool since then. We now measure such charge-exchange cross sections using the LLL Cyclograaff facility and the 16-detector neutron time-of-flight spectrometer.

The results of this modeling to infer neutron-scattering cross sections are illustrated in Fig. 6 for tin,² where experimental neutron-scattering data do exist. The curves are predictions based on proton scattering and charge-exchange experiments, and the good agreement with data emphasizes the utility of this method. In fact, these

results were also used to calculate neutron total and nonelastic cross sections for tin (Fig. 7, black line). The results show better agreement with existing data than do those of a global fit (blue line). (Tin is a possible component of superconductors for fusion reactor magnets.) Measurements are also currently under way in the actinide region—which is important in fission reactors—and will lead to better neutron cross sections there.

Nuclear level densities. Many of the results of nuclear modeling applications are sensitive to various input parameters. For many cases,

the density of nuclear energy levels is required as input. Although formulas exist for estimating the level density as a function of nuclear excitation energy and angular momentum, variations from nucleus to nucleus are often large enough that the formulas serve only as a rough guide. To extract the needed nuclear level-density information, we apply our nuclear modeling techniques to our experimental data. For example, to complete the extraction of the ^{88}Y destruction cross section, which is needed in nuclear weapons diagnostics, the level density of the compound-nucleus ^{89}Y is required.

Fig. 7 Neutron total and nonelastic cross sections. The black curves were calculated in the same fashion as those in Fig. 6 and reproduce the data better than calculations based directly on systematics of neutron scattering (blue curves).

This may be obtained by an analysis of the $^{87}\text{Rb}(^3\text{He},n)^{89}\text{Y}$ reaction, which at low bombarding energies is usually described by the compound-nucleus statistical model (see Fig. 2) and which can be measured at our tandem Van de Graaff facility.

In studies at LLL and at other laboratories of reactions such as $(^3\text{He},n)$, (α,n) , and (p,n) , it was discovered that the simple application of the standard statistical model was not sufficient to analyze the data and extract level densities. The reaction often does not reach statistical equilibrium in the formation of the compound nucleus, and neutrons are emitted with energies too high to be accounted for by the statistical model. These studies illustrate the need for refining the model to include so-called pre-equilibrium emission processes, which are now routinely used in many of our modeling applications.

Figure 8 shows an experimental neutron spectrum obtained at the Cyclograaff facility for the (p,n) reaction.³ The contribution of pre-equilibrium emission to this spectrum is well described in terms of the so-called "exciton model" (blue curve). This model describes a nucleus that has not come to thermal equilibrium in terms of degrees of freedom called "excitons." After this component is subtracted, the

standard statistical model may then be applied to extract accurate values for level-density parameters to be used as input for other problems. In addition, these studies indicate how to modify our modeling techniques for those cases in which the pre-equilibrium process is important.

This example illustrates the importance of experimental verification to our nuclear modeling effort. Without such verification, subtleties such as pre-equilibrium emission could have been considered of

minor significance or even overlooked, with the result that many cross-section calculations would be inaccurate, and prediction of neutron-emission spectra would be grossly incorrect.

Inverse reactions and charge-symmetric reactions

Symmetries in the nuclear dynamics sometimes allow us to measure directly the quantity of interest. For example, time-reversal symmetry, which has been verified to great accuracy in nuclear reactions, implies that a reaction and its inverse are related simply. We can, therefore, deduce a reaction such as $^{12}\text{C}(n,\alpha)^9\text{Be}$ by measuring its inverse, $^9\text{Be}(\alpha,n)^{12}\text{C}$, which, experimentally, is much easier.⁴

Less exact symmetries such as charge symmetry can also be very useful. This symmetry is most useful for light nuclei, which have a small nuclear charge and which can therefore interact similarly with protons and neutrons. For example, the disintegration of deuterium by energetic protons, $^2\text{H}(p,n)^2\text{p}$, is expected to be about the same as by neutrons, $^2\text{H}(n,p)^2\text{n}$. We have measured the spectra of the odd residual nucleon in the two cases and found it remarkably similar (Fig. 9, Refs. 5 and 6). Although the differences in the peak shape are extremely interesting for understanding the physics, the cross sections are essentially the same for applied purposes: the greater height of the peak in the neutron spectrum compensates closely for the greater peak width in the proton spectrum.

The ${}^2\text{H}(p,n)2p$ data of Fig. 9 are in fact extrapolations from measurements at 16 and 19 MeV to provide the comparison at 14 MeV where the ${}^2\text{H}(n,p)2n$ measurements were made. Thus, by appropriate nuclear modeling, we often can infer accurate neutron cross sections from other data for different reactions even at different energies. By investigating the applicability of charge symmetry and the energy dependence of nuclear models, we gain confidence in how well these principles can be applied generally.

Conclusion

Nuclear modeling is indispensable for obtaining needed cross sections where experiments alone will not supply the information. Our experimental facilities allow us to test different model calculations to verify their applicability and accuracy. This capability has been important in our present program, which includes: a study of reactions on nuclei near mass 90 of importance to thermonuclear-explosion diagnostics; charged-particle measurements on heavy nuclei to deduce neutron-scattering cross sections; and a study of the systematics of gamma decay of the compound nucleus to improve our modeling of capture reactions.

For the future, our program will include:

- Experiments on particle-gamma and particle-particle correlations. These experiments allow us to approach the problems of gamma decay and nuclear level densities from another direction, testing our nuclear modeling capabilities more severely.

- Modeling destruction cross sections for heavy nuclei, with application to thermonuclear device diagnostics.

- Radiative capture of alpha particles to the same compound nucleus observed in our proton-capture experiments. These tests will yield further information on gamma-decay systematics needed for modeling neutron capture.

- Studies of statistical fluctuation effects in nuclear reactions. From these measurements we can

extract nuclear level densities to complement our other studies.

These areas will require new experimental efforts and more sophisticated model calculations. They will also stimulate improvements in our nuclear modeling capabilities so that we can provide improved data for applied programs.

Key words: fission cross section; modeling; neutron-capture cross section; nuclear cross section; nuclear modeling; nuclear reactions.

Notes and references

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Fig. 9 "Odd-particle" spectra from disintegration of deuterons by protons or neutrons, that is, the proton spectrum for ${}^2\text{H}(n,p)2n$ and the neutron spectrum for ${}^2\text{H}(p,n)2p$, both at angles near 0° . The data for the second reaction (blue curve) are extrapolations from measurements at 16- and 19-MeV incident proton energy to 14 MeV, the incident energy of neutrons for the first reaction (data points). From the principle of charge symmetry, we expect the results to be similar. Except for the higher peak in the neutron spectrum, which is compensated for by the greater width of the proton peak, the spectra are remarkably similar.

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