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E-DIVISION ACTIVITIES REPORT

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E-Division Activities Report

August 1978

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.

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INTRODUCTION

E (Experimental Physics) Division issues an annual report which describes some of the activities in the division during the preceding year. The preceding report (UCID-17271-77) was issued in August, 1977. 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. Reprints of five recent publications reporting work performed in E-Division are appended to the present report.

E-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.

Accelerators

Most of the activities of the division are centered around four accelerators: a 100-MeV electron linear accelerator (Linac), a 400-kV dc high current (25 mA) accelerator, a 6-MV tandem electrostatic accelerator, and a 76-cm cyclotron. The cyclotron can be used as an injector for the electrostatic accelerator (cyclograaff). Two additional 400-kV high current (150 mA) accelerators will become operational very soon. 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.

Although all the accelerators can serve as neutron sources most of the neutron experiments use either the Linac or the 400-kV accelerator. 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 accelerator serves primarily as an intense source 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.

As the operating staff of the 400-kV accelerators is being moved from the old to the new accelerators, the old 400-kV accelerator operates only intermittently, since the same staff now operates both the cyclograaff and the old 400-kV accelerator. During the past year the cyclograaff was scheduled for 3200 hours of operation. The tandem accelerator operated with a cyclotron-injected beam about half the time and by itself the remainder of the time. Cyclotron operation involved only protons, while the tandem by itself accelerated protons and alpha particles each 40% of the time, deuterons 5% of the time, and heavy ions 15% of the time.

During the past year a lithium charge exchange ion source was installed at the tandem for producing beams of the He and Li ions. In addition a ^3He recirculating and recovery system will permit more economical operation with ^3He beams.

During the past year the Linac was used 75% of the time for neutron physics experiments, the remaining time for photonuclear and other measurements. A new target consisting of Ta and Be plates for stopping the electron beam was installed for the purpose of increasing the neutron intensity above 10 MeV. This target is currently used for measurements of total cross sections for neutrons in the energy range 1 to 60 MeV.

An article entitled "Probing Nuclei with LLL's Electron Linear Accelerator," is reprinted in the appendix.

Intense Source of 14-MeV Neutrons

A national research facility containing two intense 14-MeV neutron sources for fusion reactor materials research is nearing completion. 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 building for this facility was completed, prototype systems of the accelerators, rotating targets, tritium scrubbers and other components were built and tested. An accelerator was assembled and tested to 400 kV without beam and operated at 250 kV with a H_2^+ beam of 40 mA. Operation was limited by the lack of shielding of the test enclosure. A 50-cm diameter target was tested at 5000 rpm; the need for modifications of the original design became apparent. Tests up to 10 days of a tritium scrubber with a $H_2 - T_2$ mixture showed that it removed 99.9% of the entering tritium. Installation of the first deuteron accelerator in the new building was completed and tests of its performance were started.

The facility is described in more detail in the appended reprint entitled: "RTNS: A Tool for Studying Neutron Damage."

Space Charge Lenses

When positive ion beams with high current density are transported, electrical neutralization of the beam by low-energy electrons prevents the beam from expanding under the influence of its own space charge. Since electric fields remove the electrons which would neutralize the beam, electrostatic focusing lenses can ordinarily not be used for intense ion beams. The space charge lens redistributes the neutralizing electrons

in an optically useful way. This is accomplished by axially symmetric crossed electric and magnetic fields. Lenses based on this principle have been constructed here and at the University of Oregon in a cooperative project.

In addition to their usefulness for focusing high current these lenses do not have the astigmatism of magnetic quadrupole lenses and their other aberrations can be corrected by adjusting the electron density in the space charge trapping fields.

Tests of lenses were performed here with 30-keV protons and at Oregon with 1-MeV beams. Lens performance improves with improvement of the vacuum. At the higher pressures an instability occurred which resulted in circular motion of the focus at the magnetron frequency, near 20 MHz. This instability may be useful for beam chopping. The instability disappears at sufficiently low pressure.

Single electrode lenses show spherical aberrations, but an additional pair of electrodes gives a first order correction for spherical aberration.

EXPERIMENTAL RESEARCH AND DEVELOPMENT

Transplutonic Nuclides

The nuclide $^{242}\text{Am}^m$ is one of the major transplutonic elements of concern to such applied problems as actinide burn-up and ^{252}Cf production. The two most important parameters for determining the reactivity of a fissionable material are the fission cross section and the average number of neutrons per fission ($\bar{\nu}$). Both these quantities were measured recently relative to ^{235}U using an 800- μg sample of 99.5% pure $^{242}\text{Am}^m$. The fission cross section was measured between neutron energies of 0.01 eV and 20 MeV with an uncertainty of $\pm 5\%$ between 1 and 5 MeV and a larger uncertainty at other energies. $\bar{\nu}$ was measured between 100 keV and 30 MeV; representative uncertainties were $\pm 3\%$ at 1 MeV and $\pm 7\%$ at 5 MeV.

The total cross section of ^{241}Am was measured between neutron energies of 0.5 MeV and 25 MeV. The results set limits on the reaction cross section for neutrons and are useful for predictions of the quantities of Am and other transplutonic elements produced in fission reactors.

Neutron-Capture Gamma Rays

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. Since these cross sections cannot be measured directly, they have to be calculated from nuclear reaction models. Two approaches have been used to obtain parameters needed to perform these calculations.

In order to find the γ -ray strength function neutron-capture γ -ray spectra have been measured for several resonances between neutron energies of 1 eV and 10 keV for the reaction $^{87}\text{Sr}(n,\gamma)$. In addition γ - γ coincidences were measured for the resonance at 3.5 eV.

The second approach involves the observation of the γ -ray spectra produced in the inelastic scattering and capture of protons of energies between 3 and 8 MeV by targets of ^{88}Sr , ^{89}Y , and ^{90}Zr . The nuclide ^{88}Sr is of particular interest because proton capture by ^{88}Sr forms ^{89}Y , the same nucleus that is formed in neutron capture by the unstable nuclide ^{88}Y .

The results of the measurements can be compared with the results of calculations using nuclear reaction models. The parameters used in the calculation can then be adjusted to give better agreement with the experimental results. With improved parameters cross sections for unstable nuclides can be calculated with greater confidence.

Neutron Cross Sections

Hydrogen and helium are produced by nuclear transmutations induced by fast neutrons. These gases will produce radiation damage in future fusion reactors. In a collaboration with the University of Wisconsin we have measured cross sections for the emission of protons, deuterons, and alpha particles when 15-MeV neutrons interact with the major elemental and isotopic components of stainless steels, namely Fe, Ni, Cr, $^{54,56}\text{Fe}$, $^{55,60}\text{Ni}$, and $^{50,52}\text{Cr}$. Studies of the two copper isotopes have also been completed. Measured proton emission cross sections ranged from 45 mb for ^{65}Cu to 1000 mb for ^{58}Ni , deuteron emission cross sections were around 10 mb for all nuclides investigated, while alpha particle emission cross sections ranged from 15 mb for ^{65}Cu to 100 mb for ^{58}Ni . These results, as well as the energy distributions of the emitted particles, were compared with model calculations. On the basis of these comparisons predictions of emission cross sections for other nuclides can be made with greater confidence. The magnetic quadrupole

spectrometer used in these measurements is described in a reprint in the Appendix.

The total neutron cross section of ^{140}Ce was measured with high resolution for neutron energies between 20 and 240 keV. This study is a continuation of an earlier investigation of possible deviations from statistical theories of energy levels at closed shells; ^{140}Ce , as well as ^{89}Y studied previously, has a closed neutron shell. The results for both nuclides indicate deviations in the energy dependence of the s-wave strength function from calculations based on the optical model.

Neutron Cross Sections Deduced from Proton Experiments

Because of the experimental difficulty of performing accurate neutron scattering experiments, we have used the charge-exchange reaction 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 our earlier work with protons incident on ^{119}Sn the neutron potential deduced from our experiments agreed with available neutron data considerably better than did some widely-used neutron potentials.

A further test of the model involves the study of the excitation and decay of analogs of excited states of the target nucleus. Our previous work on even-even nuclei and odd-mass nuclei of $A \sim 60$ showed that analogs of excited states are populated by a two-step process of charge-exchange and inelastic scattering. For many nuclei the inelastic process is determined by a deformation parameter that may be measured by inelastic proton

scattering. The charge-exchange step is similar to that in which the analog of the ground state is excited. In principle the excitation of analogs of excited nuclear states can be predicted using potentials and deformation parameters determined by other experiments.

For a nucleus such as ^{119}Sn , observation of excited analogs in a (p,n) reaction is difficult because the yield is small relative to the large number of evaporation neutrons in the same energy range. The measurements may be made, however, by detecting the proton decay of the excited analog states in coincidence with neutrons of the correct energy. In order to compare the coincidence decay measurements with predictions of the two-step theory one needs, in addition, the proton decay probabilities of the states, which may be calculated approximately from the previously measured decay probability of the ground state analog and the known spectroscopy of the levels. When this was done for analogs of excited states of ^{119}Sn , agreement between theory and experiment was excellent even though no adjustable parameters were used. This agreement corroborates the neutron potential previously extracted from quasi-elastic scattering on ^{119}Sn ; other "standard" neutron potentials produced cross sections well outside the uncertainties of the measurements.

In another investigation the (p,n) reaction populating 1^+ excited states served to obtain information about inelastic scattering of neutrons to 1^+ levels. Measurements were performed on the reaction $^{58}\text{Fe}(p,n)^{58}\text{Co}$ at a proton bombarding energy of 20 MeV, neutron spectra were measured by time of flight to determine the relative cross sections for populating 1^+ levels. The results were compared with shell model calculations of the ^{58}Fe ground state and of 1^+ levels in ^{58}Co . Fair agreement between experiment and calculations was obtained when contribu-

tions of 4 particle - 2 hole and 3 particle - 1 hole states were taken into account. This investigation improves our ability to calculate neutron inelastic scattering to 1^+ states for nuclei of mass near 60.

Elastic and inelastic scattering of protons by Th and U was measured to infer 14-MeV neutron cross sections of these nuclides. These cross sections are of interest to applications to systems in which fusion neutrons are produced. The measurements used 20 and 26 MeV protons and a high-resolution broad range magnetic spectrometer.

Scattering of protons by $^{151,152,153}\text{Eu}$ was also measured. The goal of this experiment was to understand the ground state rotational band structure of ^{152}Eu which is radioactive. It was known previously that ^{151}Eu is nearly spherical while ^{153}Eu is strongly deformed. As a result of these measurements and a coupled channel analysis of the data, we found that ^{152}Eu is as strongly deformed as ^{153}Eu .

Energy Deposition by Neutrons

When neutrons pass through materials, they interact with nuclei, and some of the kinetic energy of the neutrons is transferred to kinetic energy of ionizing particles. The energy transferred to kinetic energy of charged particles per unit mass of material is called kerma, and the kerma per unit fluence is called the kerma factor. Kerma factors are used for calculations of heating produced by neutrons and for dosimetry for biomedical applications.

Kerma factors can be calculated from microscopic cross sections, but for fast neutrons available cross section information is often insufficient to permit reliable calculations.

Differential cross sections have been measured for the emission of protons, deuterons, and alpha particles, produced in the bombardment by

15 MeV neutrons of the major constituents of stainless steels, i.e., Fe, Ni, and Cr. Similar measurements were performed on Cu. From these measurements kerma factors were deduced.

In addition, an attempt has been made to measure kerma factors for 15-MeV neutrons directly for C, Mg, and Fe. Spherical ionization chambers with walls of these three materials were procured. Measured ionization currents for known neutron fluences permit deduction of kerma factors through application of the Bragg-Gray cavity ionization principle. The interpretation of the data is difficult, and further work is needed before reliable kerma factors can be deduced.

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. Measurements were carried out for spheres of several sizes made of Cu, Nb, Th, and U. Comparison of the measurements on Th and U with calculations based on evaluated microscopic cross sections showed agreement for U, but a discrepancy of the order of a factor of two for Th in the neutron energy range from 5 to 10 MeV. The calculations on Cu and Nb have not been completed. A reprint of a more detailed description of the pulsed sphere measurement is appended.

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.

Experiments with a neutron spectrum that represented both fission and fusion neutrons have been performed on fourteen materials, and over 30 radionuclides were observed. Calculations on the experiments have shown problems in the commonly used calculational procedures: a mistake in the interface between one neutron flux calculation and the activation calculation results in errors of up to 70% in (n,γ) reactions, another error is introduced by setting the production of isomeric levels equal to that for the ground state, and some cross sections are incorrect. Nevertheless, some cross sections and calculational procedures give results that agree with experiment for some isotopes.

Photonuclear Reactions

Monoenergetic photons from positron annihilation in flight were used to measure photonuclear cross sections of ^{13}C and ^{18}O for photon energies up to 42 MeV. The results for the photoneutron cross section of ^{13}C disagreed with previously reported measurements, and the new result may be compared with more confidence with theoretical calculations. In the case of ^{18}O both photoneutron and photoproton reactions were observed. The energy dependence of the cross sections showed considerable structure. The distribution of

isospin strength for the giant dipole resonance of ^{18}O agrees with theoretical predictions. Comparison with corresponding results on ^{16}O indicates that ^{18}O does not behave like an ^{16}O core with two weakly bound neutrons, a model that fits other data well.

Atomic Physics

The principal activity in atomic physics has been the study of atomic inner-shell vacancies in ion-atom collisions when energetic heavy ions pass through solid targets. Because of the high density of the target a large fraction of the ions have inner shell vacancies and the ions undergo many collisions within the spontaneous lifetime of a vacancy. These collisions reduce the lifetime of the vacancies and produce broadening of the emitted x-rays. Broadening of about 100 times the natural width has been observed. Ion-solid interactions permit the study of collision processes that occur in high-temperature, high-density plasmas.

Another type of measurement was performed at the Super-HILAC where ions of Fe, Kr, and Nb were accelerated to energies of 8.5 MeV/nucleon. X-ray spectra emitted when these ions passed through thin carbon foils were obtained with a curved crystal spectrometer or a solid state detector. The aim of the measurements was to determine the relative probability for producing lithium-, helium-, and hydrogen-like x-ray emitting states, to identify the principal features of the x-ray spectra, and to measure accurately the energies of the x-ray transitions. The measurements agree with recent theoretical calculations within the experimental error (± 10 eV).

Hydrogen Depth Profiling

Measurements of the distribution of hydrogen isotopes as a function of depth in the material were described in last year's report (UCID-17271-77, p. 15). A reprint of a more detailed description of this work is attached in the Appendix.

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, protons are sometimes used to simulate the effect of neutrons since energetic protons and neutrons are expected to produce similar radiation damage.

In experiments using either neutrons or protons radiation damage is detected by measuring the lifetime of positrons introduced in the damaged area. Cu samples were irradiated with 14-MeV neutrons up to a fluence of $5 \times 10^{16} \text{ cm}^{-2}$ and with protons up to a fluence of 10^{18} cm^{-2} . Ag samples were irradiated with neutrons up to a fluence of 10^{17} cm^{-2} , but the corresponding proton experiment has not yet been performed.

Although there was similarity in the result obtained for Cu with neutrons and protons, some important differences have emerged, suggesting that there may be effects resulting from relaxation of the damage or resulting from dose rate dependence in the type of defect which is obtained.

Samples provided by investigators at LLL and other laboratories have been irradiated at the intense source of 14-MeV neutrons (RTNS-I) to investigate the effect of the neutrons on materials of interest to the design of fusion reactors. Three types of investigations were carried out during the past year: Superconducting wires were irradiated at 4.2 K to study changes in critical currents and temperatures. Pure crystals were irradiated to study changes in optical properties. Specimens of stainless steel were irradiated to study changes in tensile strength.

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. The initial experiments were carried out with large spherical copper cavities at room temperature. Techniques for electromagnetic field alignment and separation of degenerate modes have been developed. An experimental arrangement has been set up for exciting large superconducting cavities at several watts of rf power with provisions for measuring the stored energy. A superconducting resonator is being fabricated.

Safeguards

Because of the growing concern about the possibility of diversion of plutonium from reprocessing plants there is an increasing activity in safeguards at several laboratories. At Livermore the safeguards effort involves a method based on x-ray fluorescence analysis for the nondestructive assay of uranium and plutonium. This method should provide accurate, fast and inexpensive assays in a reprocessing plant. The most critical location in the fuel cycle for these measurements is the dissolver solution in the accountability tank at the input end of the light water reactor fuel reprocessing plants.

We have completed the evaluation of a type of analysis using lithium-drifted silicon detectors. This method appears to be most suitable for use in the reprocessing plant analytical laboratories. The advantage of the

method is high accuracy and easy accommodation of a wide variety of samples, its disadvantages are the need for personnel access to the detectors and relatively slow speed.

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 consist of small spheres filled with a DT mixture.

A number of x-ray and neutron detectors are available to analyze the time dependence, the energy distribution, and the spatial distribution of the emitted radiations. The detectors include a neutron and gamma time-of-flight set up, x-ray pinhole cameras, PIN silicon detectors, a bent crystal, and a window-less XRD detector.

When three DT-filled microballoons were placed in the focus, evidence for the production of 14-MeV neutrons was obtained, but the results were not reproducible. Consequently the aim of the program has been changed to the investigation of the rapid transfer of energy from the magnetic field into plasma producing high temperatures and superthermal particles.

Neutron Diagnostics for Fusion Experiments

Measurement of important plasma parameters in fusion experiments is made difficult by high densities and large volumes which prevent the escape of atoms and ions from the central regions. Determinations of neutron yields should permit deduction of information regarding primary plasma para-

meters such as temperature, density, spatial and temporal distributions. Development of diagnostic capabilities is carried out in cooperation with the Princeton and Livermore magnetic fusion groups.

A detector has been developed to measure total neutron yield during a short pulse of 2.5- or 14-MeV neutrons. It has high sensitivity (20 cm^{-2} minimum) and large dynamic range (up to 10^7 cm^{-2}). A neutron spectrometer system has been developed for continuous sources in the 0.5 - 20 MeV range. It has an energy resolution of 160 keV at 2.5 MeV and 550 keV at 14 MeV. Measurements made with this system may be carried out on a single 0.5-sec source pulse at detector count rates up to $7 \times 10^5 \text{ s}^{-1}$. The spectrometer system distinguishes neutrons and gamma rays, is small, and may be used behind a collimator.

A study is underway to establish minimum requirements for a neutron diagnostic system for toroidal or mirror fusion experiments. Results indicate that neutron spectrum measurements with modest energy resolution (200-600 keV at 14 MeV) permit the determination of the impurity concentration in a plasma heated by two opposed neutral beam injectors.

Study of 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 and oxygen (in the form of carbon dioxide) produced at the Linac as tracers to measure changes in ventilation and clearance rates.

Four men were exposed to 0.4 ppm ozone for 2 hours during intermittent exercise sufficient to quadruple total ventilation. Within 4 minutes

of the start of exercise arterial oxygen decreased during inhalation of ozone and the effect remained for some time after the exposure had ended. The results suggest mechanical changes in the central and peripheral airways caused by ozone.

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PHYSICAL SCIENCES AND ENGINEERING

Probing Nuclei With LLL's Electron Linear Accelerator

Linear accelerators help expand our understanding of basic nuclear phenomena. This understanding yields many benefits: we can use it to design superior nuclear weapons or to improve our knowledge of materials for nuclear reactors. We use the LLL 100-MeV electron linear accelerator—*linac*—for a variety of applications, such as measuring neutron cross sections, producing gamma rays to make radioactive isotopes, and generating positrons for photonuclear experiments.

The LLL electron linear accelerator—one of our basic tools for studying the atom's nucleus—accelerates primary beams of electrons up to energies of 100 MeV. The electron beams are then directed onto one of several kinds of production targets to generate secondary beams of neutrons, high-energy gamma rays, or positrons.

Our 100-MeV linac is a source of abundant neutrons that simultaneously covers ten orders of

magnitude of neutron energy (from 10^{-3} to 10^7 eV). This feature is especially important to those LLL programs that depend on a knowledge of neutron cross sections. Other types of neutron sources produce more intense beams in narrower energy regions; for example, the Rotating Target Neutron Source produces neutrons in a narrow energy range near 14 MeV. However, a linac has the significant advantage of making simultaneous measurements over a broad neutron energy range at a single facility.

LLL's 100-MeV electron linac belongs to a class of accelerators that ranges from small medical and radiographic machines (with a few-MeV energy limit) to the 2-mile-long giant at the Stanford Linear Accelerator Center (with an energy capability of 20 000 MeV). The energy range chosen for a research accelerator mainly depends on the characteristic energies of the phenomena studied. Thus, machines designed for subnuclear particles (such as Stanford's linac) need energies in the low thousands of MeV. In contrast, machines that search the nucleus (such as LLL's linac) use secondary beam energies up to about 50 MeV.

While ultrahigh energies are not needed for most

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Fig. 1. The Livermore electron linac. Compacted gravel, 3.7 m thick, shields the aboveground area from the linac's radiation. A thick concrete block wall isolates the accelerator cave on the right from the experimental caves. In these experimental caves, secondary beams of gamma rays or neutrons are produced. A removable converter can be placed at the output end of the accelerator to produce positively charged electrons (positrons), which in turn produce gamma rays in the experimental caves. Beam transport systems carry the electrons to any of the five neutron- and gamma-ray production areas (four underground, one aboveground).

nuclear experiments, we do need high beam power. Our linac reaches instantaneous levels of nearly 1000 MW in the short beam bursts of some experiments. Its average beam power is 10 kW under these conditions.

During the 25-plus years of electron linac existence, experimenters in many laboratories have applied these machines in research stressing the interaction of *electrons* with nuclei. However, at LLL we have used secondary beams rather than such primary beams. With our present linac, as well as with its smaller (40-MeV) predecessor, we have mainly focused on the interactions of neutrons and gamma rays with a wide range of nuclei. Our linac's primary electron beam serves merely as a convenient energy source to produce these secondary beams.

LINAC OPERATION

We placed our linac about 8 m below ground (Fig. 1) to contain the intense radiation from the secondary beams. An elaborate system of controls and interlocks further protects workers from accidental radiation exposure.

The electrons to be accelerated originate from the hot cathode of a pulsed electron gun (Fig. 2). The pulse duration can be varied from a few nanoseconds to a few microseconds, depending on experimental requirements. Our 14-m-long linac accelerates the electrons to full energy in seven stages.

Stage one occurs in the gun, where a high-voltage supply accelerates the electrons to an energy of 0.1 MeV. Electric and magnetic fields subsequently focus the electrons in a buncher cavity. This second-stage system breaks the beam up into millimetre-

Fig. 2. Schematic of the linac system. Electron acceleration begins in the gun on the far right of the accelerator cave. In the bunching system, faster electrons catch up with slower ones to produce successions of electron bunches. Each of the succeeding waveguide sections further accelerates the electron bunches. Klystrons, amplifiers that operate in the microwave region, are housed above each waveguide to provide the microwave power to boost the electromagnetic waves traveling the length of the accelerator. The electrons lock on to these waves, which are moving at almost the speed of light. At the output end of the accelerator, the transport system brings the particles to the bending magnets (not shown). From here, a primary beam of electrons, or a secondary beam of positrons from a positron converter, can be sent to the neutron- or gamma-ray-production areas.

long bunches by rejecting out-of-phase electrons and then accelerates the electrons to a velocity of 0.985 c (where c is the speed of light) at departure.

The beam is further accelerated by the electromagnetic waves in the five main linac sections. Each of these sections is a 2.3-m-long copper waveguide operating at a microwave frequency of 2855 MHz. Klystrons, housed above each accelerating waveguide, supply the necessary microwave power, which can be adjusted to control the energy gain of the electrons. In the waveguides, the advancing electromagnetic wavefronts accelerate the electrons. The electrons, which enter the first waveguide at 0.985 c , leave the final section at 0.99999 c and with an energy of about 100 MeV.

After the electrons leave the waveguides, one of two sequences may occur. The primary electron beam can be guided straight into a room containing a neutron-production target, bent 28° to the left to a second neutron-production target (both below ground), or bent vertically into a neutron-target silo for aboveground experiments. Experimental sites can be located in any of nine neutron flight paths coming from the target production areas. These beam tubes, ranging in length from 3 to 250 m, are used to provide energy selection by time-of-flight dispersion of the neutrons.

Alternatively, the electron beam may be intercepted by a target of material with a high atomic number, such as tungsten or tantalum, which

produces positrons. The positron beam can be routed into one of two experimental caves containing gamma-ray-production targets for experiments on photonuclear reactions—interactions of photons with nuclei.

NEUTRON PRODUCTION

For neutron experiments, we typically operate the linac in a mode that produces a primary electron beam with an energy of 100 MeV. This beam comprises 1440 pulses per second of electrons, each with a pulsewidth of 10 ns. Magnetic fields guide the primary electrons to water-cooled production targets of tantalum, which convert most of the electron energy to high-energy gamma rays. We optimize the target thickness so that a large fraction of these gamma rays interacts within the same target and produce neutrons from the nuclei. Collimators then restrict the neutrons within a narrow, parallel beam along one of the nine evacuated pipes, which lead to more than fifteen experimental stations below and above the ground.

Our linac produces a neutron beam with a continuous energy distribution, or a "white" spectrum of neutrons. All the neutrons are produced within a very brief period, coincident with the electron pulse incident on the production target. Because of the velocity distribution of the neutrons produced, such a narrow pulse allows us to use time-of-flight

techniques to accurately obtain neutron energies.

Reliable neutron-induced cross sections are essential to a number of LLL programs, both in weapons and nonweapons applications. As well, the rates at which breeder reactors produce fissionable uranium or plutonium isotopes depend on these cross sections. Many cross sections, if known at all, have large experimental uncertainties, and a better definition of them would help us solve a number of practical problems. With our linac, we conduct numerous cross-section measurements that yield basic data for solutions of a variety of problems.

Fission Cross Sections. We have used time-of-flight techniques to perform neutron fission cross-section measurements on various nuclei. In particular, we have measured the neutron-induced fission cross sections of uranium-235 to an accuracy of 2% for neutron energies of 0.8 through 14 MeV. Figure 3 illustrates the data obtained during a single linac experiment.

The uranium-235 nucleus is especially important because it serves as the main fissionable element in many reactors and weapons systems and as a standard element for obtaining other fission cross sections. It is in this latter application that we measured the fission cross sections of a variety of uranium, plutonium, americium, and thorium isotopes relative to the fission cross section of uranium-235. Flight paths ranged from 15 to 34 m. Figure 4 shows the fission cross-section *ratio* of plutonium-239 to uranium-235. Using two similar detectors (one each for plutonium and uranium), we measured the ratio of the fission rates at a given energy. Since we had already measured the fission cross section of uranium-235, we could deduce the plutonium cross section from this ratio. This method was also used for the other isotopes mentioned above.

Fission cross sections of many of the transplutonic nuclides are extremely difficult to measure: the isotopes are scarce, and samples are often too small to be measured using conventional techniques. Using the 3-m linac flight tube, in which the neutron flux is the highest, we recently applied a special, highly sensitive technique to measure the cross section of a 3- μ g sample of curium-245—a

Fig. 3. Fission cross section of uranium-235 as a function of neutron energy. This measurement gives us the probability of fission reactions occurring over a given range of neutron energies. All the data points shown were obtained during a single linac experiment. The experiment conducted on time-of-flight paths 60 m long spanned the energy range 0.8 to 14 MeV with an accuracy of 2%.

Fig. 4. Fission cross-section ratio of plutonium-239 to uranium-235. Using two similar detectors (one for plutonium, the other for uranium), we measured the ratio of fission rates at a given energy. Since we already knew the fission cross section of the uranium, with the above ratio we could deduce the plutonium cross section. The solid line depicts the previous estimate of the ratio.

sample over 1000 times smaller than those used to measure the more common fissile elements.¹ Our measurements yielded new results in the neutron energy range between 0.01 eV and 35 eV.

Currently we are measuring the fission cross section of another transplutonic element, americium-242m. Its nucleus has an unusually high thermal fission cross section ($7 \times 10^{-25} \text{ m}^2$). We are using a specially designed hemispherical ionization chamber to detect fission fragments in the presence of copious alpha particles from the decay of the curium-242 daughter of americium-242m. Without the use of the special ionization chamber, these alphas would obscure the measurements of the fission fragments. The fission cross-section measurements will cover a wide range of incident neutron energies—from 0.01 eV through 20 MeV.

For americium-242m, we are also measuring the number of neutrons emitted per fission as a function of incident neutron energy, $\bar{\nu}(E_n)$. These measurements cover the energy range from 100 keV through 20 MeV. The ratio of $\bar{\nu}$ for americium-242m to $\bar{\nu}$ for uranium-235 is about 1.35. We measure $\bar{\nu}$ by requiring coincidence between a fission fragment detected in the ionization chamber and a neutron detected in a proton-recoil counter.

Neutron-Capture Cross Section. In conjunction with our neutron time-of-flight techniques, we have used several means of detecting the gamma rays resulting from radiative-neutron capture. To measure total capture cross sections, we used liquid-scintillator detectors which are sensitive to gamma rays but insensitive to the details of the gamma-ray spectrum.

We used this technique to measure the capture cross sections of plutonium-239 over broad ranges of neutron energy. The capture cross section proved to be considerably larger than the value obtained in older measurements, which only yielded the cross section averaged over neutron energy. When plutonium-239 is used for the fuel in breeder reactors, it is important that as many neutrons as possible be available for the breeding process. This larger capture cross section implies that more neutrons are unavailable for breeding. Our result, in conjunction with other measurements, was an important con-

tribution to the facts that led to the decision to stop development of the gas-cooled breeder reactor.

We also measured capture cross sections for gold-197 and holmium-165, which are useful as capture cross-section standards. Measurements on barium-130, tellurium-128, and tellurium-130 provided crucial answers to anomalies in lunar geology studies; measurements on osmium-186 and osmium-187—used as a radioactive clock to measure the age of the solar system—helped make astrophysical dating methods more precise.

In addition to measuring total neutron-capture cross sections, we have measured the details of the spectrum of gamma rays emitted during neutron capture. The excellent energy resolution of a spectrometer consisting of a lithium-drifted germanium detector with a surrounding sodium iodide anticoincidence counter allowed us to determine the intensity of individual transitions between states in the excited nucleus. With such information, we could test various nuclear models that have been proposed to describe the neutron capture process. For example, recently measured gamma-ray spectra from neutron capture on tantalum-181 (at incident neutron energies between 2 and 10^5 eV) suggest a deviation from the statistical processes usually associated with γ -decay in heavy nuclei.

Neutron Total Cross Sections. In yet another approach to neutron measurements, we determined neutron total cross sections. Using the short-beam-burst (5-ns) capability of the LLL linac, we measured high-resolution neutron total cross sections with detectors at the end of the aboveground 250-m flight tube. Such experiments served as a sensitive probe of the validity of the statistical nuclear model. For instance, in a recent experiment on the closed-shell nucleus of yttrium-89, it was found that the behavior of the neutron-nucleus interaction as reflected in the level densities deviated from the standard statistical model.

GAMMA-RAY PRODUCTION

Our linac also contributes to experiments with secondary beams of gamma rays. For example, we produce high-energy bremsstrahlung to make

radioactive isotopes for nuclear medicine. In the mode for maximum beam power, our linac can provide average beam currents of nearly 1 mA in an electron beam with an energy ranging from 30 to 100 MeV, consisting of 300 pulses per second, each with a 3- μ s duration. A platinum production target is generally used to optimize the bremsstrahlung flux.

High-energy bremsstrahlung has been used to produce radioactive isotopes of oxygen and nitrogen, which are useful in life-process studies on dogs. In particular, these radioisotopes have permitted the *in vivo* monitoring of lung damage resulting from ozone inhalation. The decay products of nitrogen-13 were detected by a special multiscintillator positron camera built at LLL. Figure 5 shows the spatial distribution obtained. Preliminary results indicated a significant improvement in the ability to detect ventilation changes in the lung due to ozone inhalation.

POSITRON PRODUCTION

In the production of positrons, the primary electron beam strikes a conversion target usually placed at the output end of the accelerator. This heavy-metal (usually tantalum or tungsten) positron-production target generates bremsstrahlung, and a significant fraction of these photons forms electron-positron pairs in subsequent interactions within the same target. The target thickness is chosen to maximize the yield of positrons. A magnetic beam-transport system filters out all particles except those in a narrow, selected momentum band. In some experiments, the positrons are accelerated first to higher energies before momentum selection is made.

These positrons are used to produce monoenergetic gamma rays for photonuclear (photoneutron and photofission) experiments. In-flight positron annihilation in a second converter target produces gamma rays with a well-defined energy slightly greater than the positron energy. The gamma-ray energy can be tuned to satisfy the demands of the experiment. Monoenergetic gamma-ray intensities obtained with this technique at LLL have been among the highest in the world. We have

Fig. 5. Spatial distribution of nitrogen-13 in a live dog's lung as "seen" by an Anger positron camera. The colors indicate different concentrations of the nitrogen-13 isotope within the lung. Time-dependent, local changes in the ventilation caused by air pollutants, e.g., ozone, can be detected with this technique.

used them in a systematic study of photoneutron reactions in about 65 isotopes.

Our photonuclear program at the 100-MeV linac has recently emphasized the study of the fission process induced by gamma rays (photofission). In collaboration with Los Alamos scientists, we have investigated eight nuclei so far: thorium-232, neptunium-237, plutonium-239, and five isotopes of uranium. Figure 6 shows the fission cross section of uranium-238 decomposed into (γ, f) and (γ, nf) components in the 6- to 18-MeV range. The (γ, f) notation means that gamma rays impinged on a target and that fission resulted (first-chance fission); the (γ, nf) notation means that fission resulted after neutron emission (second-chance fission). By using photons to initiate fission, we can study those processes in nuclei that are difficult or impossible to study with neutron-induced fission. The data from Fig. 6, for example, may be used to infer the neutron-induced fission cross section of uranium-237. This inference is necessary because the half-life of uranium-237, about seven days, is too short for

Fig. 6. Photofission curves showing decomposition of uranium-238 into first- and second-chance fission components. The upper curve represents fission initiated by gamma rays without the intervening emission of neutrons (γ, f); the lower curve represents fission after ejection of neutrons (γ, nf). The second-chance (γ, f) fission cross sections may be used in inferring the neutron-induced fission cross sections of uranium-237, an isotope too short-lived for direct measurements.

us to use it as a neutron target. Furthermore, the data from photofission are, in principle, easier to compare with the predictions of theoretical models.

These examples of measurements with the high-intensity beams of our 100-MeV linac indicate the variety of applications made possible by this versatile machine. By providing data for both basic research and applied problems, this accelerator will continue to be a vital tool for our scientific community.

Key Words: electron linear accelerators; fission cross sections; gamma rays—production; linac; linear accelerators; neutron cross sections; positrons.

NOTES AND REFERENCES

1. For more information on fission cross sections, see the June 1977 *Energy and Technology Review* (UCRL-52000-77-6), p. ii.

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RTNS: A Tool for Studying Neutron Damage

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RTNS: A Tool for Studying Neutron Damage

The high fluxes of 14-MeV neutrons produced by fusion reactors cause materials damage problems that affect reactor feasibility, economics, and safety. Although a body of neutron damage data has been developed in the fission reactor program, we need still more information to guide materials selection for the first demonstration fusion reactor.

We have been studying damage processes induced by 14-MeV neutrons for approximately four years at LLL's RTNS-I (Rotating Target Neutron Source). The RTNS-I is the most intense 14-MeV neutron source in the world, producing 6×10^{12} 14-MeV neutrons per second. By extrapolating the technology of this source, we have designed a facility with two new neutron sources (RTNS-II) to produce 4×10^{13} neutrons per second. Construction of these sources and the research facility that houses them is nearing completion. The new facility will be operated by LLL as a national center for fusion reactor materials research.

The successes obtained with magnetic confinement of plasmas in tokamak devices, first in the Soviet Union and then in the United States, led in the early 1970's to the decision to accelerate the U.S. program to produce fusion power reactors. The resulting effort was structured into two subprograms: one to address the remaining physics uncertainties

of plasma confinement and the other to address the engineering feasibility of fusion reactors. Of the engineering problems associated with fusion reactors, one of the most difficult to study without having a working fusion test reactor is the damage produced by the 14-MeV neutrons from the T(d,n) reaction.

In any of the currently proposed magnetic or inertial confinement fusion reactors, the flux of 14-MeV neutrons at the inner wall of the reactor will be about 10^{14} n/cm²·s. Although this flux is over an order of magnitude below that typical in fission power reactors (1 to 3×10^{15} n/cm²·s), the average energy of fission neutrons is so much lower (below 1 MeV even for fast breeder reactors) that the damage processes may be significantly different. This difference in energy prevents us from extrapolating confidently from fission reactor experience.

Neutrons damage reactor materials in several ways. Energetic atoms recoiling from collisions with neutrons produce cascades of vacancies and interstitial atoms in the material lattice. Helium and hydrogen are produced when neutrons interact with atoms of the material through (n,α) and (n,p) reactions. Vacancies may aggregate into voids, gas bubbles may form and grow, and interstitial migration may change alloy microstructure. These processes result in changes in the physical and electrical properties of materials. Materials such as superconductors may fail, or the strength of structural or radiological-containment components may be reduced below an acceptable level. Near the surface of the material, energetic recoil atoms may escape

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completely (sputtering) or the lids of gas bubbles may break off (exfoliation). Release of such material into a plasma could cool it and quench the thermonuclear burn. Gross modification of surface features causing increased gas absorption or release, insulator failure, or damage to the final optics of lasers could have similarly unacceptable results.

LLL's involvement with intense 14-MeV sources began in 1966 with the installation of the ICT (Insulating Core Transformer) accelerator (Fig. 1). As originally installed, this 400-keV air-insulated machine could produce an 8-mA beam of atomic deuterons (D^+). By bombarding a target of tritium absorbed in titanium, we could produce a 14-MeV

Fig. 1. Deuteron accelerator for the RTNS-I source. The large aluminum high-voltage terminal on the left contains the deuteron ion source and the power supplies that drive it. In operation, this machine accelerates a 400-keV deuteron beam through an accelerating column that is surrounded by cylindrical rings to produce a smooth electrostatic surface. The 400-keV deuteron beam then passes from the diffusion pump stand at the center of the picture through the evacuated-beam transport system out to the right to the target room in which the rotating tritium target is placed.

Table 1. Livermore neutron source parameters.

	RTNS-I 1976	RTNS-II 1978
Beam energy, keV	400	400
Target current, mA	25	150
Spot size, mm	6	10
Target diameter, cm	23	50
Target speed, rpm	1100	5000
Source strength, n/s	6×10^{12}	4×10^{13}
Maximum flux, n/cm ² ·s	1.7×10^{12}	1.0×10^{13}
Target lifetime, hr	100	100

neutron source strength of 2×10^{12} n/s. To prevent the power deposited in the target from raising the temperature to such an extent that excessive tritium is released, we rotate the target at 1100 rpm with its back surface in water. Although this source was developed primarily for weapons-related neutronics work, interest in fusion materials damage problems led to its upgrading in the early 1970's. By 1974, a source strength of 6×10^{12} n/s was produced with a peak flux of 1.7×10^{12} n/cm²·s available.

Using the RTNS-I source, experimenters from LLL and other laboratories measured sputtering coefficients, hardening of metals (measured by change in yield strength of sample), and change of critical current in superconductors resulting from 14-MeV neutron irradiation. The results of these measurements indicate that damage processes that depend on total defect production scale about as expected with neutron energy. Damage processes dependent on the type and distribution of clustered defects do not scale as expected. Change in lattice parameters, detailed microstructure, yield strength, superconducting properties, and optical absorption do not scale with damage energy deposited. Although these experiments were hampered by the low flux available (maximum fluence to date in an experiment has been about 2×10^{17} n/cm²), their results demonstrated that simple extrapolation of fission reactor experience is inadequate for fusion reactor design decisions.

To provide for fusion neutron irradiations and to overcome the flux limitations of the RTNS-I

Fig. 2. The recently completed facility for RTNS-II.

source, in 1973 LLL proposed the construction of a new neutron source facility containing two improved sources based upon the rotating target technique. Design source strength was projected at 4×10^{13} n/s with a peak flux of 1.0×10^{13} n/cm²·s. LLL proposed to operate this facility, called the RTNS-II facility, as a national center for fusion reactor materials research under the auspices of the Office of Fusion Energy.

The main parameters of the RTNS-II neutron sources are compared to those of the RTNS-I source in Table 1. The estimated cost of construction of the new facility and the neutron sources is \$5 million. This funding was provided as a line item in the FY 1976 federal budget. Design of the facility began in March of 1976; procurement began in May of that year and construction started in August. We estimate that the project will be completed in July of 1978.

RTNS-II FACILITY

Physical Plant. The physical plant for the RTNS-II Facility serves two functions: to contain the primary and secondary radiation resulting from operation of the neutron sources and to provide control and support areas for work on both unirradiated and irradiated components of the sources and experimental apparatus. The facility is shown in Fig. 2. The primary radiation from the neutron sources will be contained by concrete walls 2.5 m thick around the target rooms in which neutrons are produced. (The door to one of the target rooms is

shown in Fig. 3.) Access to the accelerators, target rooms, and hot work areas of the facility is limited and controlled by the source operators.

To minimize the dangers of handling irradiated equipment, we provide a hot cell and hot work room for servicing and storing these activated materials. Activated apparatus is moved from the target rooms to the hot cell by a remote handling system able to place a 3-Mg package with 0.5-cm accuracy. Because the tritium targets outgas approximately 370 GBq (10 Ci) of tritium per hour during normal operation, the exhaust of all vacuum systems on the accelerators must be collected and passed through a tritium scrubber. This scrubber converts all hydrogen isotopes to water and traps the water for safe disposal.

Accelerators. The major components in one accelerator and target room are shown in Fig. 4. A

large high-voltage terminal contains the deuteron ion source plus the power supplies and vacuum pumps required to operate this source. The high-voltage terminal is raised to 400 kV by a 300-mA Cockcroft-Walton high-voltage supply. Power to operate the ion source and all the electronic components in the high-voltage terminal is provided by a 75-kW isolation transformer that feeds three-phase power from ground into the terminal. The ion source selected for these accelerators is a modification of the reflex arc MATS-III source developed at Livermore as an injector for magnetic confinement experiments. A 90° double focusing magnet is used following the source to separate the D^+ beam from the molecular beam components (D_2^+ , D_3^+) that are also produced by the source. This arrangement allows the accelerating column and the beam transport system for the accelerator to be optimized for a

Fig. 3. Shielding door to one of the target rooms in the RTNS-II facility. The door is about 2.5 m thick, 3.5 m wide at the outside, and 2 m wide on the inside face. This door swings on hinges and weighs approximately 44 Mg. When in use, experimental equipment and target assemblies for the RTNS-II sources will be moved from a hot work area through this door into the target room for irradiation under remote control. During this process, the door will be operated from a remote location.

Fig. 4. Major components of a single neutron source in the RTNS-II facility. On the left (in the machine room housing the accelerator) are the stepup transformers and rectifier stacks, the high-voltage terminal containing the deuteron ion source for the accelerator, and the accelerating column and beam transport system. In the cutaway room at the right of the figure are located the rest of the beam transport system, the rotating target, and the cart on which the experimental package is placed. Shown at the extreme right is the remote transport system that moves experimental and target packages to and from the target room. Components shown in dashed lines can be added to upgrade the high-voltage supply to 500 mA rating.

single ion species.

A cutaway view of the high-voltage terminal (Fig. 5) shows the ion source and the accelerating column through which the ion beam passes as it moves from the 400-keV terminal to ground. The vacuum envelope of the acceleration column was fabricated at LLL by vacuum-brazing alumina insulating rings to copper electrodes. The active length of the column (the region through which the beam actually accelerates) is shorter than the outside length of the envelope (25 cm vs 80 cm). Intermediate electrodes of copper coated with chrome are used to connect the outer copper electrodes (to

which the resistor string is connected) to the inner molybdenum electrodes that shape the field in which the deuterons are accelerated.

A major design problem in the construction of the RTNS-II neutron sources is to minimize the possible consequences of the ion beam from the accelerator being misdirected onto a component of the accelerator. Since the power density of this beam is 75 kW/cm^2 , the beam will melt any material on which it is directed except for the rotating target. Our solution to the problem is to design the acceleration column and beam transport system to deliver to the target virtually all of the ion beam in-

Fig. 5. Major components of the ion source and acceleration tube of the RTNS-II sources. The ion source is mounted vertically to allow installation of a 90° bending magnet that separates unwanted molecular components of the beam from the atomic components. After this separation the deuteron beam accelerates from the extraction voltage (15 keV) to the full 400-keV energy by passing through the accelerating column of the machine. The large gas load from this ion source (approximately 10 to 20 cm³/min at standard temperature and pressure) is removed from the vacuum system by three turbomolecular pumps—each with a capacity to pump 2000 litres of air per second.

jected into the accelerating column. Limiting apertures of pyrolytic graphite are used at places in the beam transport system where the ion beam is diffuse. These apertures can stand power deposition of a few kW/cm² and are thus useful to limit the outer edge of the ion beam. Diagnostic devices that determine the beam current and beam position without interacting with the beam have been developed. Beam current is monitored by measuring the dc magnetic field produced by the beam. Beam position is determined by viewing the recombination radiation produced when the beam ionizes residual gas in the beam transport system.

To test the design of the many accelerator subsystems, we conducted a full-scale test with one accelerator (Fig. 6). Because the test enclosure does

not have neutron shielding, the beam accelerated must be H₂⁺ rather than D⁺. (For purposes of testing the accelerator, these two beams are equivalent.) Tests of all accelerator systems to date have been successful. Ion beams of up to 50 mA have been produced at energies up to 250 keV. Noninteractive beam-monitoring devices have been tested successfully, as has the design of the ion source acceleration column and beam transport system. Tests using a deuterium-loaded rotating target are to begin shortly.

Target System. Although we are investigating materials with better hydriding and thermal properties, the initial neutron source for the RTNS-II will be the tritium-in-titanium material used on RTNS-I. To ensure that this material operates in

Fig 6. High-voltage terminal and power supplies of the prototype accelerator. To the left are the insulating legs, capacitors, and rectifier stacks that comprise the Cockcroft-Walton power supply. This power supply is connected to the skin of the high voltage terminal by a high-power 10 000- Ω resistor, which decouples the terminal from the power supply during sparks. The acceleration column and beam transport system (not shown) for this prototype accelerator are located behind the high-voltage terminal at the back of the enclosure.

the same thermal cycle on RTNS II, we have modeled the thermally driven process of tritium dissociation and diffusion in the target. Time-dependent temperature profiles of the energy deposition in the target were calculated using the power density of the beam, the dwell time of the beam on the target element, and the thermal conductivity of both target material and backing. Using these profiles, we calculated the dissociation of titanium tritide and the diffusion of tritium through the target to its front surface. To normalize this calculation to the target lifetimes observed on RTNS-I, we added to the calculation a measured surface barrier

to tritium release. The condition under which the target must be operated on RTNS-II was determined by adjusting the speed of the beam past each target element until the tritium release over each thermal cycle was the same as that calculated for RTNS-I. To accommodate the increase in power density from 30 kW/cm² on RTNS-I to the planned 75 kW/cm² on RTNS-II, we had to increase the target speed from 1100 cm/s to 10 000 cm/s.

This tenfold increase in target speed was accomplished in two steps. The first was to increase the speed of target rotation from 1100 rpm to 5000 rpm

Fig. 7. Prototype of the 50-cm, 5000-rpm target system. The test target is mounted on the cart that will be used to carry the target system and experimental apparatus to and from the target room. During irradiation the target assembly is aligned to within 1 mm of the target surface, which is moving at 5000 rpm.

by replacing the present rotating vacuum seal of stainless steel on plastic with a differentially pumped air-bearing seal. The second step in increasing the target speed was to double the target diameter to approximately 50 cm. A full-size test of this system is shown in Fig. 7. The test target is mounted on a prototype of the cart that will be used to carry experimental apparatus and the target to the target room.

To circulate cooling water across the back of the target, we placed the water within etched channels in the back of the target. A section of the mask used

to etch these channels is shown in Fig. 8. After etching, another sheet of copper is bonded over the channels, and the target is then hydroformed to the desired shape. Target backing materials and the processes of etching, bonding, and hydroforming have been extensively tested in the past two years. All steps of the sequence required to produce 50-cm targets have now been demonstrated.

One remaining detail of the tritium-in-titanium target is poorly understood. During the 100-hour usable lifetime of the target, over twice as much deuterium is injected into the titanium by the deu-

Fig. 8. A section of the etching mask used to produce water-cooling channels within one of the rotating targets. The target is made by etching the dark lines of this pattern into one sheet of copper alloy and then diffusion-bonding another sheet of copper alloy over it to produce a sandwich target with water channels inside the back of the target material. Cooling water is supplied from and returns to a central hub. To remove the 60 kW of power that the ion beam deposits on the tritium target, water must be forced through these channels at a rate of approximately 1 litre/s. The convoluted channels enhance heat transfer to the coolant.

teron beam as the original tritium inventory of the target. However, deuterium is released from the target by diffusion at a rate over 10 times that at which tritium is released. The distribution of tritium remaining in the target is quite nonuniform as a function of depth in the target and is not that expected from any simple model in which equilibrium mixing and diffusion of hydrogen isotopes is assumed. Successful operation of the RTNS-II sources depends upon the persistence of this behavior at the higher deuteron dose⁴ levels the target will experience on RTNS-II.

OTHER NEUTRON SOURCES

Two alternative neutron sources for fusion materials studies are currently being considered by the Office of Fusion Energy. The first, referred to as INS (Intense Neutron Source), has been authorized for construction at the Los Alamos Scientific Laboratory. This source would focus a 1.5-A beam of T^+ on a supersonic target of D_2 gas to produce a total neutron source strength of 1×10^{15} n/s. Construction of this neutron source was authorized along with RTNS-II in the FY 1976 federal budget. However, because of budgetary limitations, construction of the INS has not yet begun. The current estimated cost of the INS project is \$30 million.

Another neutron source, using a different source reaction, was authorized in the FY 1977 federal budget for construction at the Hanford Engineering Development Laboratory at Hanford, Washington. This source would use a 35-MeV deuteron linac and a liquid-lithium target. Bombarding the lithium target with a 100-mA beam of deuterons can produce a total neutron source strength in excess of 10^{16} n/s. The neutrons produced range in energy from less than 1 MeV up to a maximum of about 45 MeV. However, the neutron spectrum has a mean energy of about 14 MeV with a broad maximum near that energy. Such a neutron spectrum may be an acceptable approximation to the spectrum in a fusion reactor. The projected cost of this neutron source is \$83 million. Operation is scheduled for five years from the start of construction, which has not yet begun.

These sources may be compared by noting that

the experimental volume of the RTNS-II sources is 2 cm^3 , that of the INS is 10 to 50 cm^3 , and that of the $Li(d,n)$ source is 1000 cm^3 . Construction of the latter two sources will require advancing the technology of accelerators, beam transport and beam diagnostics, and targets.

FUTURE DEVELOPMENTS

With initial operation of the first of the two neutron sources in the RTNS-II Facility scheduled for July of this year, the experimental program in the new facility will begin. First regularly scheduled materials experiments are planned for October of 1978. The size and extent of this experimental program will depend upon future budgets for the fusion program. The RTNS-II sources were designed with options that allowed them to be upgraded to source strengths of 10^{14} n/s. Such upgrading would extend the period of usefulness of these sources to the late 1980's.

If the neutron sources are not used to capacity by the fusion materials program, experiments in areas such as neutron cancer therapy or technology development for other accelerator-related programs may be possible. The design tools and diagnostic concepts developed during the RTNS-II project may be applicable in areas as diverse as the development of neutral beam sources or direct energy conversion devices for fusion reactors, or the production of high-current pulsed injectors for radiotherapy or spallation breeding accelerators. Operation of these neutron sources and participation in the new and unique materials work to be done with them will give LLL a lead role in a new area of technology.

Key Words: fusion reactors; neutrons—radiation effects; reactor materials; Rotating Target Neutron Source; RTNS.

FOR FURTHER READING

Readers wishing additional information on intense sources of high-energy neutrons should see the special issue of *Nuclear Instruments and Methods*: "High Energy and High Intensity Neutron Sources," *Nucl. Instrum. Methods* **145**, No. 1 (1977).

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The Magnetic-Quadrupole Spectrometer: Studying Neutron Reactions

We have developed a magnetic-quadrupole spectrometer to measure the charged particles from nuclear reactions induced by 14-MeV neutrons. A magnetic lens focuses the charged particles from the reaction site onto a distant detector. This protects the detector against neutron bombardment and greatly improves the signal-to-background ratio. We are using this spectrometer to assess potential radiation damage problems in fusion reactors of the future, to measure the energy deposited by neutron-induced reactions in biological systems, and to study the interaction between two neutrons. This same principle has been adapted to the measurement of fast charged particles from laser-induced fusion.

A serious obstacle to achieving economic electrical power from fusion reactors is the damage to reactor components that could be produced by the

high neutron flux. The 14-MeV neutrons from the $D + T \rightarrow n + \alpha$ reaction have much greater radiation-damage potential than the neutrons from present fission reactors; at comparable power, a fusion reactor will produce more neutrons, and they will have higher average energy. At these higher energies, nuclear reactions that deposit hydrogen and helium in structural materials are much more probable. Both gases can significantly weaken the materials. To assess the magnitude of this radiation damage, we must know the probabilities or cross sections of these nuclear transmutations.

In many cases, the best way to measure these cross sections is to detect the energetic nuclei of hydrogen (protons, deuterons, and tritons) and of helium (alpha particles and helium-3 ions) that result from the interaction of fast neutrons with materials. If the material is thin enough, i.e., a foil, then the charged particles lose little energy before they escape from it. A detector viewing the foil can count directly the numbers of hydrogen and helium nuclei formed. At the same time, an appropriately

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chosen detector can measure the ions' energy distributions, an important bit of diagnostic data. A typical, extensively used experimental setup is illustrated in Fig. 1a.

Previous measurements of this type have been beset by a low true counting rate and by large backgrounds. The true rate is small because conventional neutron sources produce only 10^9 or 10^{10} neutrons per second and because the target foils must be thin. The backgrounds are large because neutrons and gamma rays from the source interact

strongly with the detector itself. Shielding between the source and the detector helps, but there is seldom enough room in this geometry to shield the detector well.

Under the sponsorship of ERDA's Division of Physical Research, we have developed a magnetic-quadrupole spectrometer that focuses charged particles from the target foil onto the detector (Fig. 1b). Even though the detector is farther from the target foil, the focusing section of the magnetic lens significantly increases the detector's effective solid

Fig. 1. Experimental setups for measuring charged particles from neutron-induced reactions. (a) Former method, with the charged-particle detector close to the foil under neutron bombardment. The detector here receives all charged particles within its acceptance solid angle, but its proximity to the foil makes it hard to shield it adequately against background radiation such as neutrons and gamma rays. (b) Present technique, with a magnetic quadrupole lens focusing the charged particles onto the detector.

Fig. 2. Overall view of the quadrupole spectrometer, removed from the intense neutron source. The cylindrical target chamber at the right contains the foils to be bombarded with neutrons. Charged particles from the resulting reactions go down the long evacuated tube, through the triple quadrupole magnet array, and into the detector chamber (left).

Fig. 3. Working parts of the quadrupole spectrometer. In the front row, left to right, they are the target wheel with a selection of four different target foils, the first charged-particle collimator, internal shielding for the detector, a pair of collimating apertures, and the adjustable detector-telescope holder. Behind, the copper rod supported on thin wire legs is a shadow bar that is placed on axis to reduce the background of neutrons, gamma rays, and charged particles other than those of the selected energy.

angle. Neutrons and gamma rays, on the other hand, are unaffected by the lens. They disperse and become less troublesome as the square of the distance between the neutron source and the detector. Also, we can put much more shielding between the source and the detector to reduce the background still further. Even the material of the magnetic lens itself doubles as a neutron shield. These modifications improve the signal-to-background ratio by more than a factor of thirty.

The other key element in our experiments is the LLL rotating target neutron source (RTNS), the world's most intense continuous source of 13- to 15-MeV neutrons. This source produces 4×10^{12} neutrons per second, or perhaps 400 times more than sources typically used in such experiments. The quadrupole lens and selected shielding materials allow us to use this source at its full intensity without destroying the radiation-sensitive detectors.

Quadrupole magnets have been used before to focus nuclear-reaction products. What is new is applying them to studies of neutron-induced reactions. The combination of this spectrometer and the intense neutron source gives us a unique capability.

For the spectrometer's many advantages, we pay a small price. At any one setting of the quadrupole lens, only a part of the spectrum is focused onto the detector. We must change the magnetic field strength to observe different parts of the spectrum. In a sense, the lens acts as a band-pass filter with a fairly large band width. However, we can scan a complete charged-particle spectrum with only a few magnet settings.

The assembled spectrometer is shown in Fig. 2. In operation it is moved so that the target foil inside the cylindrical target chamber (right) is near the source. The charged particles travel in the evacuated tube through the quadrupole magnets and focus on detectors at the left end of the spectrometer. Typical target foils, silicon surface-barrier detectors, collimating apertures, and shielding materials from the inside of the spectrometer are shown in Fig. 3.

Figure 4 is one of our measured spectra: protons from aluminum bombarded with 15-MeV neutrons. We expected a continuous spectrum like this, but we

were surprised to find it extending clear down to 800 keV. It used to be very difficult to measure below 2.5 MeV, but this caused no concern because no one expected to find many protons there. Our data now show that, for aluminum, neglecting the protons below 2.5 MeV can lead to errors of 40% in the total hydrogen-production cross section.

Table 1 is a brief summary of some of our results at 15-MeV neutron energy. The correction to 14 MeV, the mean energy of fusion neutrons, is straightforward and small. Different fusion-reactor component materials yield widely differing amounts of hydrogen and helium by nuclear transmutation. Each material, of course, reacts differently to hydrogen or helium implantation, and these differences are being studied by metallurgists. Our cross-section data tell the metallurgists how much of these impurity gases to expect in fusion reactor components, giving them a sounder basis for assessing materials damage.

A second facet of radiation damage begins when one atom is knocked out of its lattice site. As it slows down in the material, it knocks other atoms out of their lattice sites, forming a track of displacement damage.

Such recoiling atoms have extremely short ranges, compared with hydrogen and helium ions, and almost none escapes from the foil. We can study them only by proxy, by measuring the energies and angular distributions of hydrogen and helium ions and calculating from these measurements what the recoiling-atom energy spectrum must be. Knowing the energy spectrum, we can calculate the displacement damage according to an approximate theory. Figure 5 is a spectrum of recoiling atoms from alpha-particle-producing reactions in stainless steel.

Our data deal only with primary recoil atoms from nuclear reactions that produce hydrogen or helium ions, of course, and this is only part of the total recoil-atom spectrum. It is an important part, however, because it includes all the reactions that produce helium ions. These recoils have the highest energy, so they individually cause the most displacement damage.

Fig. 4. Spectrum of protons from aluminum bombarded with 15-MeV neutrons, with the detector placed at 75° to the incident neutron direction. A few representative error bars are shown.

Beyond determining specific cross sections and recoil energy distributions, our measurements help to validate or refute nuclear-reaction model calculations. Correct calculations are essential to the fusion reactor program because we need much more nuclear data than could be produced by even a very ambitious measurement program. Only calculations can fill in the gaps between the measurements. Our cross sections and energy spectra have already been used to assess the validity of three different codes that calculate these reactions.

Another application of these measurements involves the heat released in a material by charged particles as they slow down. The charged particles' initial energy is important when calculating heating

Table 1. Summary of hydrogen and helium production cross sections at 15-MeV neutron energy.

Material	Production cross section, fm ² (10 mbarn)	
	Hydrogen	Helium
Aluminum	42.4	12.1
Titanium	12.8	3.1
Vanadium	9.8	1.7
Stainless steel 316	26.0	4.8
Copper	25.1	3.4
Niobium	5.9	1.5

Fig. 5. An energy spectrum of atomic recoils from (n,α) reactions in stainless steel (SS-316) bombarded with 15-MeV neutrons.

rates in different regions of a fusion reactor. It is also important in weapons design and, on a microscopic scale, in understanding the biological and therapeutic effects of radiation.

As an example of the latter application, fast-neutron therapy has been successful in treating certain human tumors. Part of its success is attributed to a particular interaction of neutrons with carbon nuclei in the tissue, a reaction that disintegrates the carbon nucleus into three alpha particles. To understand the biological effect of the resulting energetic alpha particles, we must know the distribution of their initial energies. We are measuring this distribution directly with our spectrometer.

The spectrometer also improves the resolution of nuclear experiments, allowing fundamental new work in nuclear physics. In one such experiment, we measured the proton energy spectrum following the breakup of deuterons by 14-MeV neutrons. The reaction also gives off two neutrons, which go

Fig. 6. An energy spectrum of protons from the $D(n,p)2n$ reaction — deuterium bombarded with 14-MeV neutrons — compared with a theoretical calculation. The agreement is fairly good in general, but the departure near the peak of the smooth curve suggests that the theoretical treatment may be neglecting some significant factor.

undetected. Their interaction in the final state, however, strongly influences the shape of the proton spectrum. Measuring the shape of the spectrum, therefore, gives strong evidence of the neutron-neutron interaction.

Good resolution is essential in this measurement. The low background of our spectrometer allows us to use detectors of exceptional resolution. These detectors would be destroyed if they were not well shielded from the neutron source, and the quadrupole-spectrometer geometry makes this possible.

The resolution we obtained was 2.2 times better than any previous measurement. Figure 6 shows our data, superimposed on a theoretical calculation. The fine difference at the peak between our data and the theoretical curve indicates that modifications are necessary either in our conception of the neutron-neutron interaction or in the complex three-body theories used to calculate the final state interaction.

During the spectrometer's development, we realized that a similar technique could be used to focus the fast charged particles from laser-fusion experiments. This case presented the problem of overcoming a large background of x rays and at the same time increasing the signal (alpha particles from the thermonuclear burn). Quadrupole lenses installed on the Argus experiments at LLL are successful in significantly increasing the signal-to-background ratios.

We are continuing to develop our spectrometer with the goals of increasing its effective solid angle and the width of its band pass, and of reducing the background. We began with a quadrupole doublet lens but found a triplet lens (Figs. 1 and 2) superior. We have made most of our measurements with silicon surface-barrier detectors. For certain experiments, however, proportional counters or scintillation detectors may be preferable. In collaboration with a group from the University of Wisconsin, we are developing these improved techniques that should yield cleaner data in an even shorter time. These new techniques will make possible many more experiments on charged particles from fast-neutron interactions.

Key Words: alpha particles; charged-particle detectors; deuterons; fast neutrons — cross sections; fusion reactors; materials — effects of radiation; protons; spectrometer — quadrupole.

Pulsed Sphere Measurements for Weapons and Fusion Reactor Design

Pulsed sphere measurements provide a way of validating the Monte Carlo transport codes and the input cross sections used in the design of thermonuclear weapons and fusion reactors. In these measurements pulsed 14-MeV neutrons are generated at the center of spheres of materials to be investigated, and the emitted neutron spectrum is measured by time-of-flight techniques. The measurements described in this article cannot reproduce the complex conditions found in weapons and fusion reactors. However, agreement between measurement and calculations for a simple geometry and one material (or simple composites) is a necessary prerequisite to reliable fusion reactor calculations.

Early in 1967 we started the pulsed sphere program in response to the needs of the weapons programs at the Laboratory. Through the years, pulsed sphere measurements have had an appreciable impact on the calculations carried out for both nuclear weapons and fusion reactor design. The program studies how well the transport codes used in these calculations reproduce the 14-MeV integral measurements of the neutron and gamma emission spectra of materials considered in the design of weapons and fusion reactors.

The conceptual design of fusion and fusion-fission reactors raises many questions concerning

how thermonuclear neutrons (14-MeV energy) interact with reactor materials. Thermonuclear neutrons are much more energetic than those arising from the fission process, and the nuclear interactions of these particles are not understood as well as those of fission neutrons. Nevertheless, if we are to effectively shield a fusion reactor's superconducting magnet, blanket, and first wall from radiation damage, we must not only be able to calculate accurately the transport of such neutrons in reactor materials, but we should also have some method of checking the reliability of the calculations.

The pulsed sphere program involves pulsing the center of spheres of a given material (or simple composites) with 14-MeV neutrons and observing at a distant point the arrival time of the emerging neutrons—time-of-flight (TOF) technique. The secondary gamma rays generated by the neutrons are also measured. While traversing the spheres, the neutrons may be affected by elastic and inelastic collisions or absorbed in a variety of nuclear reactions. The arrival time "signature" of the neutrons, which is sensitive to the nuclear cross sections of the materials, can be directly compared to the transport code results. Discrepancies, if any, point to the need for further cross-section measurements, revision of the theoretical assumptions and approximations introduced in the code, or possible code errors. For example, during the course of this program, we found that previous calculations of inelastic scattering cross sections for high-energy neutrons neglected several significant physical processes. To remedy

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the situation, we included those processes in the cross-section evaluations used in our neutron transport codes, greatly improving their accuracy. As a result of such corrections, a tool is being made available for more reliable design of controlled thermonuclear reactors.

EXPERIMENTAL PROCEDURE

We produce fast neutrons of roughly 14 MeV by the nearly isotropic $T(d,n)\alpha$ reaction. The 400-keV deuterons used in this reaction are produced by the Livermore insulated-core-transformer (ICT) accelerator. The deuteron beam, pulsed and bunched, impinges upon a tritium-titanium target, which is mounted at the end of a low-mass assembly and positioned at the center of the sphere to be measured. The 2.06-cm-diam titanium layer, in which the tritium is diffused, is evaporated on a tungsten backing 0.051 cm thick. Neutron production is monitored by counting the recoil alpha particles with a thin (about 50- μ m) lithium-drifted silicon solid-state detector set at 174° with respect to the deuteron beam line. The materials to be studied are machined into solid spheres or into overlapping sets of spherical shells, with a truncated cone opening into which the low-mass tritium target assembly is inserted. A

schematic drawing of the experimental setup is shown in Fig. 1.

The neutron and gamma-ray spectra are measured with TOF techniques, where the flight path is about 10 m long. For neutron spectra measurements, the energies of the emitted neutrons are determined by measuring the time differences between the neutron arrival times at a distant detector and the creation time (that is, the moment at which the deuteron beam pulse strikes the tritium target). In experiments examining the spectra of high-energy neutrons (between 2 and 14 MeV), we focus a 2.5-MHz pulsed beam with a bunched pulse width of about 1.5 ns on the tritium target. For low-energy neutrons (between 10 keV and 1 MeV), we use 1- and 10-kHz pulsed beams with unbunched pulse widths variable between 100 ns and 10 μ s. The arrival times for the high-energy neutrons are obtained by monitoring the recoil proton pulses generated by the neutrons in a liquid organic scintillator (NE 213). For low-energy neutrons, we use a ^6Li -loaded glass scintillator in which the alpha and triton particles from the $^6\text{Li}(n,\alpha)t$ reaction generate the arrival time signals. The gamma-ray spectra between 250 keV and 10 MeV are also measured with NE 213 scintillators. However, since secondary

Fig. 1. Schematic drawing of the experimental setup. The 400-keV deuteron beam strikes the tritium-loaded target at the nose of the narrow cone embedded in the spheres. The resulting flux of roughly 14-MeV neutrons is slowed and attenuated by nuclear reactions in the spheres. Plastic scintillators in concrete shielding at the ends of TOF paths detect the transmitted neutrons.

Fig. 2. Raw time-of-flight neutron spectra. (a) Neutron blank run spectrum, which includes only the neutrons from the tritium target and the gammas from the low-mass assembly. (b) Neutron spectrum from a 5-mean-free-path copper sphere (radius = 20.3 cm). Time of flight increases from right to left with zero time slightly to the right of the γ_1 peak. The gammas, with the shortest time of flight, arrive first, followed by 14-MeV neutrons and then slower neutrons. The 14-MeV peak is strongly attenuated in the experiment with a copper sphere in place. A second gamma peak, γ_2 , results from the next beam pulse. In (b) the data collection time was 15 times longer than in (a).

gamma rays travel at the speed of light and arrive at the detector at the same time, we cannot measure their energies by their time of flight. Instead, we infer their spectrum by measuring the energies of the Compton electrons that are produced by the gamma rays in the scintillator. The measurement is made by performing a pulse-height analysis on those Compton electrons that fall within the envelope of the

gamma TOF peak (that is, a pulse-height analysis of TOF peak-gated pulses).

Figure 2a shows the raw time-of-flight spectrum from the $T(d,n)\alpha$ reaction. Since no spherical assembly has been positioned around the tritium target, this is called a blank run. The spectrum shows gamma rays and 14.7-MeV neutrons emitted by the tritium target assembly, as well as background gamma radiation emitted at random times by the activated environment viewed by the detector. The two gamma-ray peaks shown correspond to gamma rays produced from two adjacent beam pulses: the first beam pulse produces the first gamma peak, γ_1 , and the neutron peak; γ_2 is produced by the next beam pulse. The gamma-ray peak and the time-independent capture-gamma-ray background are suppressed relative to the neutron peak by the use of electron-proton pulse shape discrimination. Rejection of gamma pulses is possible electronically since electron recoil scintillations (induced by gamma rays) differ in pulse shape from proton recoil scintillations (induced by neutrons).

Figure 2b shows a raw TOF spectrum from a 5-mean-free-path copper sphere (20.3-cm radius). The main difference between this spectrum and a blank spectrum (Fig. 2a) is that the 14-MeV neutron peak is attenuated and a spectrum of neutrons below the source energy is generated by neutron interactions with the copper nuclei. The abscissa shows the channel number, and the ordinate shows the raw number of counts in each channel. Since the pulsed beam frequency is 2.5 MHz, the time between the two gamma-ray peaks corresponds to a period of 400 ns. The measurement of this period calibrates the TOF for each channel. Since gamma rays travel at the speed of light, time zero is displaced to the right of the gamma peak by L/c , where L is the flight path and c is the velocity of light; in Fig. 2, time zero is to the right of γ_1 .

Figure 3a shows a typical TOF measurement of a high-energy neutron spectrum from a 1.6-mean-free-path lithium sphere (25.52-cm radius). The abscissa shows the time of flight in nanoseconds; the ordinate shows the ratio between the counts per nanosecond to the total number of counts in the neutron peak when the sphere is removed (Fig. 2a).

Fig. 3. Measured neutron spectra for 1.6 mean free paths of ^7Li . (a) Time-of-flight spectrum. (b) Energy spectrum. The transformation to the energy spectrum permits the results to be interpreted without information on the detector efficiency or the flight path length.

We have normalized the data so that the ordinate shows counts/ns/source counts, where source counts represent the number of 14-MeV neutrons produced at the tritium target. This number is determined by first finding the ratio of alpha particles to neutrons on a blank run (without the sphere). Next, we repeat the run with the sphere in place and record the alpha particles produced during the measurement. Since the ratio of alphas to source neutrons will be the same in both measurements, we can then infer the number of 14-MeV source neutrons produced when the sphere is positioned at the tritium target (see Fig. 1).

The measured neutron time-of-flight spectra are converted relativistically to energy spectra to simplify comparison with the energy spectra calculated by the time-independent transport method used at other laboratories. Figure 3b shows the energy spectra for the 1.6-mean-free-path ^7Li sphere.

DISCUSSION

We compare the measured neutron TOF spectra and the gamma-ray spectra with the spectra calculated with a coupled neutron-photon Monte Carlo transport code, TARTNP. This code is a modified version of TART that is used only for neutron transport. The variations in energy (between 13.8 and 15.1 MeV) and intensity of the ICT neutron

source between 0 and 180° (as much as 15%) are taken into account in the calculations. The low-mass target assembly, the detector collimator, and the air between the spherical targets and the detector are programmed into the Monte Carlo calculations.

Fig. 4. Comparison of the measured and calculated neutron time-of-flight spectra for 2.9 mean free paths of iron. The calculations were done with the revised LLL ENDL neutron library and the ENDF/B-III library. Such spectra as these revealed the importance of including direct reaction processes for inelastic scattering of fast neutrons.

In the pulsed sphere program, we have measured the neutron TOF and gamma-ray spectra from a large number of materials ranging from lithium to plutonium. Among these materials, ^6Li , ^7Li , Be, Al, Ti, Fe, Cu, Nb, and Sn are of direct interest to the magnetic and laser fusion programs. Cu, Nb, and Ti are used in the winding of superconducting magnets that confine the plasma, and Nb has also been suggested as a structural material for the tritium-breeding blanket. The measurements on fertile materials such as ^{232}Th and ^{238}U can be used to test the design accuracy of hybrid reactors in which a fertile blanket partially or totally surrounds the fusion cavity. Such hybrid reactor designs have been calculated using neutron libraries such as the Evaluated Neutron Data Library (ENDL) available here at LLL and the ENDF/B libraries, versions III and IV, compiled by Brookhaven National Laboratory.

To illustrate the power of the method exemplified by the pulsed sphere program, Fig. 4 compares the measurements of a 2.9-mean-free-path iron sphere with the calculations based on the ENDL and ENDF/B-III libraries. The good agreement between calculation (using LLL cross sections) and measurement shown in Fig. 4 resulted after revision

of the cross sections listed in the Livermore library. The large discrepancies that appeared when ENDF/B-III cross sections were used in the calculations for iron were also observed in all comparisons made for elements throughout the periodic table between aluminum and lead. When the new version of the Brookhaven neutron library was developed—the ENDF/B-IV version—these discrepancies were corrected. The main source of the discrepancies between measurements and calculations using the old ENDL and ENDF/B-III libraries was the inaccurate theoretical description of 14-MeV inelastic neutron scattering. At energies as high as 14 MeV, direct and pre-equilibrium processes have become important and must be included with the compound processes to give an accurate description of the interaction. Neglect of the first two processes resulted in an underestimate of the high-energy inelastic neutron scattering cross sections, thereby producing the discrepancies noted above. For lighter nuclei such as Li, Be, C, and N, where the main contribution to inelastic scattering comes from the direct process, the discrepancies observed between measurements and calculations resulted from a poor representation of the cross sections for inelastic scattering (both magnitude and angular distribution) to

Table 1. Measured and calculated integrals with versions III and IV of the ENDF/B library for the neutron emission spectra in the energy intervals 10 to 15 MeV, 5 to 10 MeV, and 2 to 5 MeV. (The integrals are expressed in terms of emitted neutrons/source neutrons.) With the improved ENDF/B-IV cross-section library, the Monte Carlo calculations agree much better with the experiments.

Material	Thickness, mfp	Energy interval, MeV	Measured integral ($\pm 7\%$)	Calculated integral	
				TART ENDF/B-III	TART ENDF/B-IV
Titanium	3.5	10 to 15	0.01271	0.02284	0.01315
		5 to 10	0.00211	0.00067	0.00163
		2 to 5	<u>0.00799</u>	<u>0.00596</u>	<u>0.00614</u>
			0.02281	0.02947	0.02092
Iron	4.8	10 to 15	0.005853	0.005629	0.004883
		5 to 10	0.001102	0.000523	0.000971
		2 to 5	<u>0.004455</u>	<u>0.002300</u>	<u>0.003643</u>
			0.011410	0.008452	0.009497

low-lying levels of the target nucleus. Revision of the cross sections in the ENDL library has also improved agreement with measurements for the lighter nuclei.

Table 1 shows the improvement obtained with ENDF/B-IV cross sections. It gives the measured and calculated integrals of the emitted TOF spectra with versions III and IV of the ENDF/B library for titanium and iron. The emitted spectrum has been divided into three neutron energy intervals: 2 to 5, 5 to 10, and 10 to 15 MeV. The integrals are given in emitted neutrons per source neutron; the error in the measured integrals is less than 7%. Overall, the new version IV reproduces the measurements quite well and represents a clear improvement over the ENDF/B-III library, where discrepancies of as much as a factor of two exist between the measurements and calculations.

CONCLUSION

Our measurements of the high-energy region of the neutron emission spectra (between 14 and 5 MeV) have uncovered important sources of errors in the calculations and cross sections, which caused discrepancies of as much as a factor of two between measurements and calculations for many materials. For the low-energy region of the neutron spectra (1 MeV down to about 10 keV) and for the gamma emission spectra, the calculations were in better

agreement with the measurements, with discrepancies no larger than 20 to 30%.

Measurements of neutron and gamma spectra on materials of interest to the magnetic fusion community provide checks on the codes and cross sections used in the design of conceptual fusion reactors. Agreement in the above comparisons would give us added confidence in the more complex fusion reactor calculations. The experiments are deliberately simple in design to allow close examination and criticism by the fusion community. By such means, discrepancies among calculations from different institutions may be more rapidly resolved.

Key Words: cross sections—measurements; neutron emission; pulsed sphere measurements; reactors—design; time-of-flight measurements.

FOR FURTHER READING

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PHYSICAL SCIENCES

Measuring Hydrogen-Isotope Distribution Profiles

We have developed a new nondestructive technique for measuring the depth distribution of hydrogen isotopes absorbed or implanted near the surface of any material. The method allows real-time study of the inventory and diffusion of hydrogen, deuterium, and tritium. Briefly, the technique involves bombarding the surface with a monoenergetic beam of ions chosen for their ability to react with the hydrogen isotope in question, producing fast neutrons. The energy distribution of the neutrons is a sensitive indicator of the energy of the bombarding particles at the instant of reaction, and hence of the depth of the reaction sites below the surface of the material. We have obtained a sensitivity of one part per million for tritium in copper. We are applying the technique to several energy-related materials problems.

Some materials, among them titanium, scandium, erbium, and uranium, have an affinity for hydrogen and its heavier isotopes, deuterium and tritium. This affinity can be an advantage, as in the fabrication of

titanium-tritide (TiT_2) targets for neutron production. In other cases it can be a serious disadvantage. Steel, for example, loses as much as 50% of its ductility on absorbing hydrogen, limiting its usefulness in the coal gasification program.

The inside walls of fusion reactors will be bombarded by deuterium and tritium ions, which will accumulate below the wall surfaces. In some materials, absorbed hydrogen migrates away after such implantation; in others it may stay in place. Exactly how the hydrogen moves with respect to changes in temperature, past history, radiation damage, chemical composition, and preloading with hydrogen, and how the presence of hydrogen isotopes affects such properties as strength and ductility, are of great importance to fusion reactor research as well as to our nuclear explosives programs.

We have developed a fast, sensitive, nondestructive method for measuring concentrations of hydrogen isotopes in solid materials, a method that should have wide applications. It is based on measuring the energy spectrum of neutrons produced when we bombard a hydrogen-loaded material with a beam of energetic ions. At a well-defined energy, the reaction between protons and tritons (hydrogen and tritium nuclei), for

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Fig. 1. Schematic representation of a tritium depth-profiling measurement. Protons with an initial energy E_0 interact with tritium embedded in a titanium matrix, liberating neutrons. The energy of each neutron depends on the energy of the proton that liberated it, and this in turn depends on the distance x that the proton penetrated before encountering a tritium atom. Hence measuring the neutron energy yields information about the tritium distribution with depth.

example, produces large numbers of monoenergetic neutrons. Only in those reactions that take place right on the surface can the bombarding particles have their full energy, however. As the bombarding particles penetrate below the surface, they lose energy, and this energy loss affects the energy of any neutrons they produce. Conversely, measuring neutron energy defines the energy of the particle that caused the reaction, and hence the depth in the material where the reaction took place. Measuring how many neutrons there are for each particular energy range gives us an indication of how many hydrogen nuclei were available at each depth in the material. We call this concentration vs depth a hydrogen-isotope profile.

Figure 1 outlines this process in more detail for tritium depth profiling. A beam of protons of well-defined energy E_0 , produced in an accelerator, bombards a metallic titanium target in which there is an unknown concentration of tritium at some distance below the surface. As each proton enters the titanium it begins to lose energy; in fact, the amount of energy it loses is roughly proportional to the depth as it penetrates. When the proton encounters the tritium-filled region, it has a definite probability of reacting with a tritium nucleus at some depth x and producing a neutron. This interaction probability depends on the nuclear reaction cross section (a measured, known quantity) and on the concentration

Fig. 2. A neutron velocity spectrum (left) and the tritium concentration profile that can be calculated from it (right), given the reaction cross section, the reaction kinematics, and the energy loss rate of protons in titanium.

of tritium atoms (unknown). Although a neutron might also come from a proton hitting a titanium atom, the probability of this reaction is relatively insignificant.

The neutron's energy depends in part on the energy of the incident proton, and this in turn depends on the initial energy of the beam and the energy lost in penetrating to the depth x where the neutron was produced. Neutron energy, and hence its flight velocity, is independent of how thick the rest of the target is. Because of its lack of charge, the neutron leaves the target without losing energy.

When a large number of neutron velocity measurements are accumulated, we sort them and display the result as a neutron velocity spectrum (Fig. 2). Knowing the nuclear cross section, the kinematics of the reaction, and how the proton slows

down as it goes through the target, we can program a computer to convert this velocity spectrum into a map of tritium concentration vs depth.

This technique will work with any neutron-producing charged-particle reaction. To map a hydrogen concentration, we bombard with tritium ions. To map a deuterium concentration, we bombard with deuterons. For a lithium concentration, we can bombard with protons, producing neutrons by the ${}^7\text{Li}(p,n)$ reaction.

Figure 3 is a schematic layout of our experimental apparatus. The pulsed ion source produces bunches of protons, deuterons, or tritons, as required. The ion bunches, typically about 1 ns in duration and coming every 200 to 500 ns, are accelerated to several million electron volts in the Cyclograaff tandem accelerator. A magnet sorts the ions according to momentum,

passing only those of a precisely defined energy. A feedback loop enables us to regulate beam energy to a precision of a few kilovolts.

A cylindrical electrode just in front of the target generates a timing signal when the ion bunch passes through it. Neutrons produced in the target travel a distance L , typically 1 to 10 m, to the detector, where their arrival produces another electronic signal. We measure electronically the time interval between a neutron's birth and its detection. Given the flight path L , an online computer can calculate the velocity and therefore the energy of the neutron.

With this apparatus, we can measure a profile in a few minutes to an hour, depending on the concentration. The beam energy and the neutron reaction cross section determine the maximum depth

that can be profiled. With our present equipment this depth may be up to 50 μm .

Because the neutron loses no energy to the target, the remaining target material beyond the neutron-production site does not affect the measurement and the sample may be thousands of times thicker than the maximum profiling depth. This allows us to profile self-supporting targets, small samples on thick backings, or even a piece of production material. Also, the sample need not be small enough to fit into the vacuum chamber; we can bring the probing beam out of the machine through a thin window and bombard the target in air.

One of the advantages of this profiling technique is that, except for minor radiation damage, it is nondestructive. This means that we can determine the

Fig. 3. Equipment for measuring the hydrogen-isotope depth profile in a target. The pulsed ion source provides bunches of hydrogen ions that the accelerator forms into a high energy beam. The analyzing magnet directs only those ions of a particular energy into the target chamber, where they bombard the target. Some of the neutrons fall on the neutron detector after traveling a distance L . For each neutron detected, the clock records how long it took to cover this distance. From the timing data, an online computer produces neutron energy spectra and profiles of hydrogen-isotope concentration.

hydrogen profile without sacrificing the specimen. It also means that we can follow a process, step by step, with consecutive profiles on the same specimen. We can, for example, observe hydrogen-profile changes as a function of temperature.

Another advantage is that the test involves hardly any sample handling. This greatly simplifies the problem of measuring hydrogen profiles in toxic, explosive, or radioactive materials.

In addition to flexibility, versatility, and convenience, concentration sensitivity and depth resolution are important factors in judging the utility of this technique. Sensitivity is determined by neutron

and gamma-ray backgrounds and by the radiation dose the sample can take without changing the distribution to be studied. To date we have achieved a sensitivity of one part per million for tritium in copper.

Depth resolution depends on various factors. Near the front surface of the material, it is limited by the overall energy resolution of the apparatus. As we go deeper into the target, energy straggling of the probing ion beam in the target material becomes the dominant factor. Figure 4 shows how the various factors combine to determine the overall depth resolution for deuterium in titanium. Over the first 10 μm , the depth resolution is uniform at about 0.6 μm .

Fig. 4. Factors affecting depth resolution and how they change with depth for deuterium in titanium. The incident deuteron energy is 1.5 MeV, the neutron flight path is 10 m, and the spectrometer time resolution is 1.5 ns. Similar curves, differing in detail, apply to other combinations of bombarding ion and target material. The incident beam spread makes a constant contribution regardless of depth. The spectrometer resolution becomes less and less important with depth. Beyond 10 μm , straggling, which continues to increase gradually, is the dominant factor influencing resolution. The overall resolution in this case broadens from 0.6 μm at 10 μm to 1.5 μm at 50 μm .

Fig. 5. Tritium and deuterium profiles in a titanium target after bombardment in the RTNS accelerator with 31 C/cm^2 of deuterium ions. Some of the deuterium has become implanted in the target, and some of the tritium, whose profile originally was similar to that in Fig. 2, has been replaced. Most of the original tritium is still present, however, and only a small fraction of the incident deuterium stayed embedded.

Even at $50 \mu\text{m}$, depth resolution has worsened only to about $1.5 \mu\text{m}$.

The depth resolution of our equipment is adequate for most purposes, and is at a practical optimum. None of the ways by which we might, in principle, improve resolution, such as shortening the ion-beam burst or increasing the neutron flight path, can have any effect on the ion beam's energy straggling. The improvement would therefore be marginal at best, and it would almost certainly be won at the cost of reduced concentration sensitivity.

The first application of this depth profiling technique was in our study of how bombardment with deuterons depletes the tritium bound to a titanium layer in the neutron generator target of LLL's Rotating Target Neutron Source (RTNS). Figure 5 shows depth profiles of tritium and deuterium remaining in the target after 31 C/cm^2 of bombardment. Only 15% of the initial tritium content of the target has been outgassed, while less than 10% of the injected deuterium remains. This suggests that some nonequilibrium process is at work. Evidently

deuterium is released 5 to 10 times as readily as tritium. A better understanding of this process could lead to improved target lifetime and performance.

Future developments with this technique involve an experiment with collaborators at the Los Alamos Scientific Laboratory to determine the feasibility of probing the hydrogen depth profile with a triton beam. We had a successful preliminary run, but the background was much higher than usual. We will have to improve the target chamber and the shielding before we can estimate what the ultimate sensitivity will be. Once we determine the sensitivity and limitations of this method, we plan to add a tritium source and a dedicated target chamber to the LLL Cyclograaff

accelerator and to develop suitable computer software for providing a routine analytical service.

Key Words: deuterium - diffusion; deuterium - nuclear reactions; hydriding; hydrogen embrittlement; hydrogen isotopes; rotating target neutron source; tritium - nuclear reactions.

For Further Reading

An example of tritium profiling with a proton beam is described in J. Davis, J. Anderson, and H. Lefevre, "Depth Profiling of Tritium by Neutron Time-of-Flight," in *Radiation Effects and Tritium Technology for Fusion Reactors*, J. Watson and F. Wiffen, Eds. (Oak Ridge National Laboratory, Rept. CONF-750989, vol. IV, 1976), p. 187.

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