Lawrence Livermore Laboratory

E DIVISION ACTIVITIES REPORT - FY 1976

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E DIVISION ACTIVITIES REPORT - FY 1976

ABSTRACT

This report describes some of the activities in E (Experimental Physics) Division. E Division carries out basic and applied research in atomic and nuclear physics as well as in material and biomedical sciences, centered around the Laboratory's four major accelerators. Experiments are grouped under the headings of neutron, photon, and charged-particle interactions. Investigations in this past year involved fission cross sections, nuclear reactions with neutrons, charged particles and gamma rays, integral experiments on neutron and gamma ray transport, fissile materials safeguarding, radiation damage caused by neutrons and protons, dense plasma focus experiments, inner-shell vacancies produced in ion-atom collisions, coherent bremsstrahlung, Raman scattering, and biomedical applications.

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-16904) was issued in September, 1975. Not all the activities are included every year.

E Division carries out basic and applied research in atomic and nuclear physics as well as in material and biomedical sciences in areas related to the missions of the Laboratory. Many of the activities are cooperative efforts with other Divisions of the Laboratory, and, in a few cases, with other laboratories.

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 (50 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).

The choice of experiments is often based on the availability of these accelerators and associated instrumentation. 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. 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.

GENERAL EXPERIMENTAL PROGRAM

Neutron Interactions

Although all the accelerators can serve as neutron sources most of the neutron experiments now use either the Linac or the 400-kV accelerator. The Linac permits the simultaneous study of neutrons of energies from thermal to about 30 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.

During the past year the Linac experiments with neutrons have involved measurements of interaction cross sections of nuclides ranging from hydrogen isotopes to heavy elements, gamma-ray production in isotopes of Ta and Au, and fission in uranium, plutonium and transplutonic nuclides.

The experiments with 14-MeV neutrons ranged from measurements of neutron cross sections to the effect of these neutrons on surfaces, on bulk properties of solids, and on biological systems.

Photon Interactions

Most of the 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. This unusual feature of the LLL Linac has been used for a number of years to investigate the energy dependence of photon interactions with many nuclides. Studies during the past year included photon-induced neutron and proton production in isotopes of oxygen, carbon, and osmium, and photon-induced fission.

Charged-Particle Interactions

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.

Charged-particle-induced reactions studied during the past year include neutron production by protons bombarding lithium, argon and isotopes of samarium, high-energy gamma ray production by protons bombarding calcium and yttrium isotopes, proton and gamma ray production by proton bombardment of a number of medium mass nuclides, and spectroscopic investigations of several rare-earth nuclides by deuteron stripping reactions.

DETAILS OF REPRESENTATIVE EXPERIMENTS

Fission

An accurate knowledge of fission cross sections as a function of neutron energy is essential to all applications of the fission process. Measurements of fission cross sections have been a major effort for some time. The simplest type of measurement is the determination of the ratio of cross sections. In these measurements the standard was ^{235}U , and neutron energies ranged from 1 keV to 30 MeV. The fission cross sections of the following nuclides were compared with that of ^{235}U : ^{233}U , ^{234}U , ^{236}U , ^{238}U , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu , and ^{244}Pu . There is also an attempt to perform measurements on transplutonic nuclides. Recently the fission cross section of ^{245}Cm was measured from 6 meV to 10 eV using a 3 μg sample. This measurement demonstrated that very small samples of high purity can be used.

At neutron energies between 10 keV and 1 MeV the ^{235}U fission cross section has substantial uncertainty. To reduce this uncertainty the ratio of the ^{235}U fission cross section to the disintegration cross section of ^6Li was measured from thermal energy to 1 MeV. Below 10 keV the ^6Li cross section is believed to be known to 1%, so that the ^{235}U fission cross section was determined with similar accuracy. Above 10 keV, because of a resonance in ^6Li , the uncertainty is larger.

Although the recently completed and published measurements of the energy dependence of the ^{235}U fission cross section between 1 and 15 MeV are believed to be good to 2%, the results differ by more than 2% from similar measurements at other laboratories. Further work is needed to confirm the results and remove present uncertainties, particularly near 14 MeV neutron energy. At this important energy measurements performed in different countries differ by as much as 15% although each measurement is claimed to have a much smaller uncertainty.

Besides the fission cross section, the average number of neutrons per fission ($\bar{\nu}$) determines neutron multiplication in fissile materials. This quantity was measured for ^{235}U for incident neutrons of energies between 0.1 and 10 MeV. The results agree with previous measurements. An effort is underway to look for structure in the energy dependence of $\bar{\nu}$, an effect of interest to the understanding of the fission process. A sample of about 1 mg of $^{242}\text{Am}^m$ will soon become available. The plan is to measure the fission cross section and $\bar{\nu}$ for $^{242}\text{Am}^m$.

Extensive measurements of various parameters which describe fission induced by photons have been performed for photons of energies between 5 and 18 MeV with a photon energy spread of about 0.3 MeV. Target nuclides were ^{232}Th , ^{233}U , ^{234}U , ^{235}U , ^{236}U , ^{238}U , ^{237}Np , and ^{239}Pu . Parameters which were measured were the absolute photo-fission cross section, the average number of neutrons per fission as well as the neutron multiplicity distribution, the average energy of the emitted neutrons, and the number of delayed neutrons per fission. In addition, cross sections for photoneutron emission (without fission) were measured. In most cases $\bar{\nu}$ increases with photon energy, but in ^{232}Th an energy region occurs where $\bar{\nu}$ decreases with photon energy. The results of the photo-fission experiments also yield information about nuclear structure, especially the shapes of the heavy nuclides.

Some years ago the discovery of fission isomers and of sub-threshold fission resonances led to a revised view of the fission process. The new phenomena were described in terms of a double-humped fission barrier. If this description is correct, one would expect that the subthreshold resonance states could decay with γ -ray emission to fission isomers. Evidence for these γ rays was obtained through the observation of low-energy γ rays emitted from the most prominent subthreshold resonance states which decay by fission, while resonance states which do not decay by fission did not show these low-energy γ rays. These observations are consistent with what one would expect if the γ rays are emitted in transitions between states in the second well of the double-humped barrier. These results help with the understanding of the fission process and thereby facilitate predictions on the fission process in nuclides for which at present direct measurements are not possible.

Neutron Cross Sections for Fusion Reactors

The size of fusion reactors is determined primarily by the maximum neutron fluence which the wall of the plasma containment vessel can tolerate during the expected time of operation of the reactor. The very large size of current conceptual designs of fusion reactors has economic disadvantages, and it is important to develop materials which would stand up under higher neutron fluences. One of the most important causes of neutron-induced radiation damage is the production of hydrogen and helium isotopes in the wall material through nuclear reactions induced by 14-MeV neutrons, so that a knowledge of the probability of these reactions is essential to the development of better wall materials. Except for reactions leading to induced radioactivities the relevant cross sections are known only in a few cases.

Observations of charged particles produced in various materials by 14-MeV neutrons have been carried out. A magnetic quadrupole spectrometer selects and transports the charged particles to a detector which can be shielded from the source neutrons. An interesting result is the observation of large numbers of low energy protons in cases where the energy balance does not permit neutron emission. For a determination of

gas production cross sections the angular distributions of the charged particles have to be measured. A combination of measurements and calculations based on improved knowledge of the reaction process will be used to determine the gas production cross sections of the elements that might be used as wall materials. For this purpose we have developed a multi-stage statistical model code which includes gamma ray decay channels at each stage of the reaction process.

Neutron Capture Gamma-Ray Spectra

The spectrum of energetic gamma rays from neutron capture is of interest both for neutron transport calculations and for estimating the effect of neutron capture on personnel. Our experiments are directed to study the complexity of neutron-gamma ray interaction in transport and capture. Special emphasis is placed on measurements of a wide range of capture gamma rays for different incident neutron energies. The gamma-ray spectra from neutron capture in tantalum were measured for neutron energies between 1 eV and 0.1 MeV. The spectra were found to be very similar at all neutron energies. Therefore, time-saving simplifications can be introduced in transport calculations.

Protons from the Disintegration of Deuterium by Neutrons

Probably the most fundamental problem in nuclear physics is the nucleon-nucleon interaction. While the interaction of protons with protons and of neutrons with protons can be observed directly, the interaction of neutrons with neutrons can be observed only indirectly. A method for doing this is to measure the spectrum of protons produced in the reaction $n+d \rightarrow p+n+n$. The interaction between the outgoing neutrons results in a peak in the proton energy spectrum. The width of this peak is determined by the strength of the neutron-neutron interaction. This is usually expressed in terms of a parameter called the neutron-neutron scattering length. Since the peak is very narrow, very good energy resolution is required for this analysis to be meaningful. Considerably better resolution than in previous measurements was obtained through the use of a magnetic quadrupole spectrometer so that one would expect that the present determination of the neutron-neutron scattering length

is very accurate. There is now, however, some doubt about the reliability of the theory used in deducing the scattering length from the data.

Neutron Cross Sections Deduced from Proton Experiments

In many cases neutron cross sections are far more difficult to measure than the corresponding proton cross sections. If one fully understands the differences between proton and neutron interactions, one can use the easier and more accurate proton measurements to deduce neutron cross sections. There are several programs for measuring relevant proton cross sections and programs to improve the understanding of the difference of the neutron and proton interactions with various nuclei.

The cross section for the radiative capture of neutrons of energies above 1 MeV is difficult to measure directly. Measurements on the radiative proton capture by ^{15}N , ^{40}Ca and ^{89}Y which have been completed have been analyzed in terms of various contributing processes. This work should lead soon to conclusions regarding fast neutron radiative capture.

For the interpretation of measurements using neutron-activation threshold detectors for high neutron fluxes emitted during short time intervals, one needs to know how many of the target nuclei were in excited states at the time of the interaction with a neutron and what the cross section of the excited nucleus is for the neutron-induced reaction. This cannot be measured directly in the laboratory because the excited states are too shortlived. The relevant information can, however, be deduced by forming the states of interest by charged-particle induced reactions. Such experiments have been carried out for nuclides of interest, *i.e.*, ^{152}Eu , ^{174}Lu , and ^{192}Ir .

To obtain a better understanding of the difference between proton and neutron interactions with nuclei, charge exchange reactions have been studied, *i.e.*, reactions in which a neutron is emitted after proton bombardment. Such reactions were studied for ^7Li and for the samarium isotopes of mass number 144, 148, 150 and 152, for the purpose of determining better the variation of the proton-neutron potential difference with energy and mass number, especially in mass regions not previously studied.

Integral Experiments

The neutron transport and resulting effects in large systems are usually calculated from microscopic cross sections. Because of the variety and large number of cross sections which are often required, integral experiments are of great importance in order 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 which 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 number and energy of the emerging neutrons is measured by their time of flight. Measurements have been performed on ${}^6\text{Li}$, ${}^7\text{Li}$ and Be, materials of interest to the fusion program, and on liquid air, because of the importance of the transport of neutrons in air. With a 7.7 mean-free-paths liquid air sphere neutron spectra and gamma ray spectra were measured. The measured neutron spectra extend down to an energy of 10 keV. The measurement agrees with transport calculations to 10%.

Another type of integral experiment is the residual radiation experiment. This is similar to the pulsed-sphere experiment but instead of neutron and gamma ray spectra, neutron-induced radioactivity is observed. The calculations based on microscopic activation cross sections can be compared with the experimental results.

In another study, neutron transport calculations were compared with observations of the transport of 14-MeV neutrons through natural uranium. There were important differences between the observed and calculated fission rates in both ${}^{235}\text{U}$ and ${}^{238}\text{U}$, and larger differences in the observed and calculated neutron leakage rates. These comparisons show clearly that changes are needed in the evaluated cross sections of uranium. Neither the LLL cross section file nor the current ENDF file give satisfactory agreement with experiment.

Safeguards

This project has the aim of performing quantitative analysis of actinides in the presence of large β and γ ray backgrounds from fission products. This is accomplished by using fluorescent x-radiation. Its

intended use is in fuel reprocessing plants. Two of the systems have been designed and constructed at LLL and evaluated at Savannah River. The result was that for a freeze-dried standard uranium solution a precision of 0.1% and an accuracy of 0.1% could be obtained in 1000 sec. Work is in progress to extend this method to measurements of hot actinide solutions without freeze-drying.

Material Science

Studies of the effect of 14-MeV neutrons on materials are conducted at the intense source of 14-MeV neutrons (RTNS). The radiation damage work is carried out by investigators from national laboratories, industrial firms, and universities, as well as by LLL staff. Experiments include the examination of exposed samples in a transmission electron microscope, studies of sputtering of materials from surfaces, measurements of electrical resistivity at low temperatures, measurements of mechanical properties after irradiation at room temperature and at high temperatures, observation of changes in superconductors during irradiation, observation of changes in optical, electrical and physical properties of glasses and ceramics.

Considerably higher fluences are readily obtainable with protons than with neutrons. There is evidence that the radiation damage produced by energetic protons is similar to that produced by energetic neutrons. Several experiments are in progress in which protons serve as a radiation source. In one of these experiments radiation damage produced by protons from the cyclograaff in polycrystalline copper is probed by measuring the lifetime of positrons introduced into the irradiated volume. Lifetimes increase with increasing radiation dose and increasing damage. The results will be compared with corresponding experiments with 14-MeV neutrons. In another experiment stainless steel wire is irradiated with protons from the cyclotron to measure radiation-induced creep. This latter experiment is being jointly funded by HEDL and LLL.

Intense Neutron Source

In March 1976 the construction of a new facility was authorized for fusion reactor materials research. This facility will contain two neutron

sources each with a design source strength of 4×10^{13} neutrons/sec. The design is based on the presently operating rotating target neutron source. This facility is intended primarily for use by investigators from other laboratories. The design of the ion source, beam transport system and target system is almost complete and preliminary measurements on components have been carried out. The accelerator will produce 150 mA of 400-keV atomic deuterons. The rotating target will have a diameter of 50 cm and rotate at 5000 rpm. Extensive tests of the rotating air bearing seal have shown it to be reliable over long periods of time. Internally cooled targets have been constructed, but so far the loading with tritium has not been as successful as for externally cooled targets. The ion source is of the multiple aperture type which has reliably produced beam currents well in excess of the present requirements. The emittance of magnetically analyzed beams has been measured, and computer studies of the electrostatics and beam optics of the acceleration tube have been completed. Operation of the new facility should begin in 1978.

Explosive Detection

For several years the Federal Aviation Administration has attempted to develop detection methods for finding explosives in baggage. Many methods have been suggested. E-Division staff have assisted in the planning and evaluation of methods based on either neutron induced reactions or x-ray fluorescence.

Dense Plasma Focus

The Dense Plasma Focus project which is based in T Division receives its technical support in E Division. The system includes a large high voltage capacitor bank which is coupled to the focus device. During the last year it was fired 1500 times in various gases. Neutron and x-ray yields were measured. For details on this project we refer to the T Division Progress Report (UCRL-50035-75).

Ion-Atom Collisions

The principal activity in atomic physics has been the study of the production of atomic inner-shell vacancies in ion-atom collisions. Because of the high probability of these processes there is the possibility of using such collisions for producing a population inversion for stimulated x-ray emission. The work is directed towards the possible application to x-ray laser schemes. For this application a knowledge of x-ray line widths is particularly important, and the widths of several x-ray emitting states were measured with an Auger electron spectrometer.

There is a large fraction of inner-shell vacancies when ions move through solid targets. For example, if 1-MeV argon ions move through an aluminum foil, on the average every ion has an L-vacancy. This high degree of vacancy production was not previously expected; thus the probability of creating a population inversion appears promising.

Coherent Bremsstrahlung from Single Crystals

Coherently produced bremsstrahlung, from both electrons and positrons, has been observed in transmission and scattering experiments in single crystals of silicon. Coherence is believed to result from the periodicity of the lattice, which permits the occurrence only of those lattice recoil momenta satisfied by both the Bragg condition and momentum conservation. A more detailed and systematic study of the phenomena of coherent radiation in the energy range from 0.1 to 10 MeV is in progress. The utility of this research is to investigate the feasibility of producing intense monochromatic, variable-energy photon beams in the MeV energy range.

Measurement of Isotopic Ratios Using Raman Scattering

A method has been developed for making rapid non-destructive isotopic analyses using Raman vibration scattering of laser beams. The method has been successfully tested on the isotope pairs $^{18}\text{O}:^{16}\text{O}$ and $^{15}\text{N}:^{14}\text{N}$ in targets of oxygen gas and air. An argon laser was used on samples with volumes $\lesssim 0.1 \text{ cm}^3$. With commercially available lasers,

isotope ratios can be measurable to an accuracy of $\sim 0.1\%$ in times of 1 to 5 min., using the Raman scattering technique. This technique represents a time-saving over conventional mass spectroscopy.

Biomedical Studies

For studies of the biological effect of neutrons the reaction Be(d,n) produced in a small accelerator is a convenient neutron source. To assist in the planning of such experiments the neutron dose rate from this reaction was measured as a function of deuteron energy. The results are consistent with expectations based on previous measurements at higher energy.

All studies of the biological effect of neutrons require accurate measurements of neutron dose. The usual procedure for measuring neutron dose is to calibrate a dosimeter with a gamma ray source of known strength and to deduce a neutron calibration from this by taking into account differences between the production and interaction of the secondary charged particles. Although the differences are small, they are poorly known. Especially uncertain is the difference in the energy needed to form an ion pair by electrons from gamma rays, and protons and heavier ions from neutron interactions. A quite different approach to calibrating neutron dosimeters is to measure neutron fluence and to calculate dose from neutron interaction cross sections. These two different calibration procedures were compared for 15-MeV neutrons and were found to agree within 6%, which is consistent with the errors in the atomic and nuclear parameters used in the calculations.

During the last four years there has been a joint program with the Department of Radiation Oncology of the University of California, San Francisco, to study the effects of 15-MeV neutrons on healthy and malignant mouse cells both in vivo and in vitro. This program is of interest both for the study of accidental or combat exposure of personnel to these neutrons and for the use of these neutrons in the treatment of malignant disease. The quantity of greatest interest is the relative biological effectiveness of neutrons relative to x-rays. In a series of experiments the following effects on cell survival were investigated:

(a) the degree of oxygenation of the cells (oxygen enhancement ratio),
(b) the temperature of the cells before neutron exposure (hypothermia),
(c) the dose fractionation, i.e., the difference in the effect of administering the same dose in one exposure and in several short exposures. In these experiments, the LLL personnel took care of the neutron source, the dosimetry, and the design and construction of collimators for the in vivo exposures.

In a cooperative program with the Department of Environmental Health and Community Medicine of the University of Washington, functional changes in the lung caused by low concentrations of ozone are studied in dogs. These experiments take advantage of the availability of radioactive nitrogen (^{13}N) and oxygen (^{15}O) at the Linac. These nuclides serve as tracers for ventilation and perfusion measurements. The most important result to date is that exposure to ozone concentrations as low as 0.5 parts per million for only a few hours results in adverse effects in the function of diseased lungs. This finding is important to the understanding of health problems in industry and in areas where ozone is produced by atmospheric photochemical activity.

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