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LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California

E-Division Progress Report FY 74

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E-Division Progress Report FY '74

The following describes some of the activities of E (Experimental Physics) Division during 1973/74. It is not intended to be a complete progress report. In particular, some of the research in pure nuclear physics and some of the work in support of other laboratory programs are not included.

Most of the activities of the division are centered around four accelerators: a 100-MeV electron linear accelerator (Linac), a 400-keV D.C. 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).

Fission

Calculations on fission chain reactions require a knowledge of the fission cross section and of the number of neutrons per fission up to the energies of fission neutrons, i.e., up to a few MeV. For systems which include thermonuclear reactions these quantities have to be known up to a neutron energy of 14 MeV. Few measurements are available for neutrons of energies between 6 and 14 MeV because of the experimental problem of producing monoenergetic neutrons in this energy region.

The LLL Linac can serve as a pulsed "white" source of neutrons. With time-of-flight techniques cross sections can be measured simultaneously over a wide range of energies. Fission cross sections have recently been measured by this method, especially in the energy region where the data were sparsest. The results showed no startling differences from accepted values, but there are some significant differences in detail. Measurements of the number of neutrons per fission as a function of the incident neutron energy are in progress, using the same white neutron source. In addition, measurements of the cross sections for the radiative capture of neutrons by ^{233}U and $^{242}\text{Am}^{\text{III}}$ are being undertaken for lower incident neutron energies because of the possible importance of this information to applications.

Although the fission process has been studied intensively for 35 years, new and unexpected aspects have been discovered in recent years. One of these has been the phenomenon of subthreshold fission, i.e., the occurrence of fission at certain energies well below the fission threshold. Related to this is the observation of delayed fission. These phenomena are being investigated with the Linac in ^{238}U and ^{242}Pu to provide more knowledge about the fission process.

The nuclide ^{252}Cf undergoes spontaneous fission with a half life of 2.6 years. The excited fission fragments emit neutrons and gamma rays. The spectrum of these gamma rays has been measured for gamma energies from 8 to 20 MeV. The results disagree with measurements at another laboratory, but agree with calculations, which also reproduce the neutron spectrum.

Neutron Transport

Neutron transport calculations usually employ neutron cross section data from a data compilation. The most widely used compilation is the "Evaluated Nuclear Data File" (ENDF). This file was developed primarily to satisfy the needs of fission reactor designers, and has in the past not been reliable in its description of the interactions of 14-MeV neutrons, especially regarding the energy distribution of secondary neutrons from inelastic collisions. At lower incident neutron energies this distribution can be described by a Maxwellian energy distribution characterized by a nuclear temperature. Experiments carried out at LLL using both incident neutrons and protons have shown that at higher incident energies the spectrum of secondary neutrons does not fall off towards high energies as rapidly as the Maxwellian distribution, but contains many more high-energy neutrons. The ENDF compilations described the secondary neutrons as Maxwellian even at 14-MeV incident energy. This caused no appreciable error for fission reactor calculations, but did not give a reliable description for fusion reactors (or for weapons involving fusion reactions).

Although information about the high energy secondary neutrons has been available from cross section measurements for a long time, the importance of these neutrons was not generally recognized, until it could be demonstrated in integral experiments, the so-called "pulsed sphere" measurements

carried out at LLL. In these measurements the spectra of neutrons emanating from spheres of various materials, one to five mean free paths thick, were studied when 14-MeV neutrons were produced at the center of the sphere. When the results of these measurements were compared with calculations based on the ENDF compilation, the discrepancy was spectacular. As a result, some of the authors of the ENDF compilations have modified their description of neutron spectra, and some of the revised compilations are in reasonable agreement with pulsed sphere results. For elements for which no pulsed sphere measurements have been performed, the ENDF compilations generally do not yet contain the appropriate revisions.

Because of the importance of concrete for shielding both for civilian and military applications the pulsed sphere technique was applied to a study of concrete. From these measurements appropriate constants for shielding calculations, especially for 14-MeV neutrons, have been deduced.

Measurements on nitrogen and oxygen have recently been performed with improved energy resolution because of the importance of neutron transport in air.

The development of a coupled neutron-photon Monte Carlo Transport Code (TARTNP) has made it possible to compare experiments and calculations on the transport of both neutrons and γ rays. The pulsed sphere method was also used for these experiments. The first study involved again nitrogen and oxygen. Preliminary experiments show more γ rays than calculated from the available nuclear data.

Nuclear Physics

Charged-particle cross sections.

For many applications calculations require the knowledge of neutron cross section that have not been measured or cannot be measured. Nuclear

models can be used to estimate such cross sections, but these models depend on empirical parameters. These parameters can be determined from measurements of neutron interactions. Neutron measurements are, however, difficult to perform with high precision, and the necessary parameters deduced from such measurements are not well known.

For some time our experimental program has been pursued at LLL in which measurements of the interaction of protons with nuclei are used to deduce corresponding parameters for neutrons. There are, however, uncertainties in this procedure. A procedure that is likely to remove some of this uncertainty is the use of charge-exchange scattering, i.e., a process in which a proton is converted into a neutron. Preliminary results show promise that this approach will be useful.

Photonuclear Reactions

The LLL Linac can serve as a source of monoenergetic gamma rays. A survey of nuclear reactions induced by these gamma rays in various nuclei has been carried out as a function of gamma-ray energy. Recently particular attention has been given to photonuclear reactions in the fissionable nuclides. Gamma rays produce neutrons both directly, and following fission. The measurements permit the determination of the number of neutrons per fission, both prompt and delayed, as a function of energy.

Nuclear Energy Levels

A knowledge of the characteristics of nuclear energy levels is necessary for the evaluation of experimental results on radioactivities induced in tracer elements. For example, the flux of high energy neutrons can be measured by the radioactivity induced by $(n,2n)$ reactions provided there is enough information available about the energy levels of the target and product nuclei. This information can be obtained by studying inelastic

scattering and reactions of charged particles. Experiments using the charged particle spectrograph are in progress on nuclides of interest to the radiochemistry effort.

Gamma Ray Spectra

The laboratory program could use better information about penetrating gamma rays produced in the capture of neutrons of energies up to 14 MeV by various nuclides. Although a number of measurements on the capture of 14-MeV neutrons have been performed at other laboratories, the results have shown large discrepancies. These discrepancies are in part due to the rapid increase of the capture cross section as the neutrons are degraded.

As an alternative way to deduce fast neutron capture information a program is underway for studying charged-particle capture, in the hope that this will permit reliable predictions of fast neutron capture probabilities and of resulting high energy gamma rays. For this purpose a large shielded gamma ray scintillation spectrometer was constructed that is capable of measuring gamma-ray energies up to 20 MeV.

Intense Source of 14-MeV Neutrons

For a variety of applications including weapons design, radiobiology, cancer therapy, and fusion reactors, an intense source of 14-MeV neutrons is valuable. At present LLL has the most intense steady source of 14-MeV neutrons. Its present source strength is about 4×10^{12} neutrons/sec and on small samples flux densities of $1-2 \times 10^{12}$ neutrons/cm²·sec can be obtained. This source is now being used more and more by scientists from other laboratories, as its existence is becoming more widely known.

Because of the importance of an intense source of 14-MeV neutrons for CTR applications plans are being made for the design of a source which produces several times higher source strength.

In the present source about 15 mA of atomic 400-keV deuterons bombard

a target of Ti in which tritium is absorbed. In order to dissipate 6 kW of beam power the target rotates at high speed and its backing is cooled by water. These targets lose tritium under bombardment. Much progress has been made in the understanding of the tritium loss mechanism and in extending the target life. In order to increase the source strength further work is in progress on suitable targets. Further work on ion sources and acceleration of ions will be needed in order to design a much more intense neutron source.

In connection with the investigation of the tritium loss under deuteron bombardment a novel way of determining the distribution of deuterium and tritium in titanium was developed. When the target is bombarded by protons of several MeV energy, neutrons are produced in the interaction of protons with tritium. The depth in the titanium, at which the reaction takes place, determines the neutron energy and from the measured neutron energy distribution the tritium distribution in the target can be deduced. Bombardment of the same target by energetic deuterons permits the observation of neutrons from the interaction of deuterons with deuterium, and hence permits also the determination of the deuterium concentration.

Fusion Reactors

One of the most serious problems for the design of a fusion reactor is the effect of 14-MeV neutrons on the first wall of the vacuum vessel. The neutrons are expected to produce embrittlement, swelling, blistering, and sputtering. For a Tokamak type reactor present estimates foresee lifetimes of the inner wall of the order of a year, but at present neither the nuclear nor the material science information is well enough known to choose a suitable wall material.

The intense source of 14-MeV neutrons at LLL has been used in an extensive program by LLL staff and by visitors from other laboratories, to investigate the effect of these neutrons on wall materials, both metals and insulators, as well as on materials which could be used for superconducting magnets. Optical, mechanical, and electrical properties have been investigated. The most extensive measurements have concerned sputtering, i.e., the ejection of chunks of material from the surface. This effect is still controversial both regarding its importance and its explanation. An effort has been made to reproduce the effect with protons.

Measurements of the nuclear cross sections for the production of isotopes of hydrogen and helium are underway. These cross sections are very poorly known and govern the occurrence of embrittlement and blistering. Here again similar measurements with protons, instead of neutrons, are much easier to perform, and permit reliable estimates of the corresponding neutron induced reaction cross sections.

Fusion reactors based on the reaction between deuterium and tritium would produce less radioactivity than a fission reactor, but the radioactivity produced by the intense neutron flux would still cause serious environmental and safety problems. It has been suggested that these problems could be avoided if a fuel could be used whose reaction products are only charged, nonradioactive particles. The reaction $^{11}\text{B}(p,\alpha)^8\text{Be}^*$ would be a possibility. The cross section for this reaction was measured for proton energies between 0.4 and 1.2 MeV and was found to be somewhat smaller than estimated from previous measurements so that its usefulness as a thermonuclear fuel is questionable.

Atomic Physics

The program in atomic physics has been concerned with the study of inner-shell vacancies produced in collisions between ions from all accelerator and atoms in solid and gas targets. Resulting x-ray and electron spectra, as well as cross sections for inner-shell excitations, have been measured.

Biomedical Applications

The interaction of 14-MeV neutrons with living cells is of interest both for the study of the effect of accidental or combat exposure of personnel to these neutrons and for the study of the use of these neutrons in the treatment of malignancies. The quantity of interest is the biological effectiveness of the neutrons relative to X rays (RBE). This quantity differs for different human organs and may depend on the radiation dose. In addition there is evidence that more densely ionizing radiation (High LET) may be more effective in destroying malignant cells than are electrons, if the cells are deprived of oxygen, as is probably the case inside a tumor (Oxygen Effect).

The availability of the most intense source of 14-MeV neutrons has made it possible to measure RBE and the oxygen effect in relatively short exposures. The biological part of the experiments has been carried out by the staff of the Department of Radiology of the University of California San Francisco. Both healthy and malignant cells were studied in vitro, and the effect of the neutrons on healthy mice as well as the effect on an implanted tumor was determined. Of particular interest to the laboratory are the observed large differences in the biological effects of 14-MeV neutrons compared to fission neutrons.

The LLL Linac can produce large quantities of short-lived radioisotopes. The uptake of ozone tagged with ^{15}O has been studied in dogs to gain information about lung function. A positron camera permits the observation of the distribution of the ozone in the body as a function of time.

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