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Technical Progress Report

NUCLEAR STUDIES USING NUCLEAR EMULSIONS

Contract Number AT (11-1)-1549

between

The United States Atomic Energy Commission

and the

University of Wyoming, Laramie, Wyoming

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I. Introduction

This report summarizes the work carried out during the past year under the Contract AT (11-1)-1549 between the University of Wyoming and the U. S. Atomic Energy Commission. Work in the development of instrumentation at the University of Wyoming for use in experiments to be done at the University of Colorado Cyclotron is included. Work completed on the analysis of experiments done at the Berkeley heavy ion accelerator is discussed.

II. Construction of External Beam Handling and Bombardment System

W. G. Simon, H. B. Eldridge, J. A. Shideler,
R. J. Jiacoletti, S. T. Ahrens

The unanalyzed beam from the University of Colorado Cyclotron has been transported from the switchyard into the neutron experimental areas as shown in Figure I-II. The essentially parallel beam, defined by the exit slits of the cyclotron, is captured and focused onto the target by the quadrupole doublet Q_5 . The currents on two pairs of slits (one vertical and one horizontal) may be monitored by using the slit box SB as shown in Figure I-III, prior to entry into the scattering chamber designated SC on the same figure.

In designing the scattering chamber every effort was made to reduce the mass present in the regions around the target and around the emulsions. This "open geometry" reduces to a minimum the effects of secondary scattering of neutrons. Construction of the scattering chamber and emulsion holders is complete. It is made from a stainless steel tube 5 inches in diameter and with 0.026 inch walls and 3 feet in length, with its axis vertical and perpendicular to the beam. The chamber was made long so that the relatively massive flanges are removed from the target-emulsion area. The beam enters and leaves the chamber through a 3/4 inch by .015 inch wall stainless steel tubes welded to the chamber.

FIGURE I-II

SCALE: 1/8" to 1'

Emulsions are placed horizontally on a 3/64 inch thick aluminum ring outside the scattering chamber at a minimum distance of 2.79 inches from the target. Cross sections for all polar angles from 13° to 167° with respect to the beam can be measured simultaneously. The emulsions must be wrapped to protect them from light with a non-hydrogenous material that is chemically inert. Platinum has been used in the past. We are using a .001 inch layer of Teflon (for chemical inertness and freedom from hydrogen) followed by a double layer of .0005 inch aluminum foil. The beam is five feet above a low-mass steel mat for minimum floor scattering.

Upon traversing the target chamber, the beam is collected in a Faraday Cup which is designated as FC on Figure 1-III. The vacuum pumping station used to evacuate the chamber and beamline is designated PS on the same figure, and an auxillary pumping station is available to pump on the system at the point where the beamline leaves the switchyard. This system, complete except for the Faraday Cup, is at present installed and evacuated.

III. Energy and Angular Distribution of Neutrons Emitted from the Interaction of 160 Mev O^{16} Ions with Nickel and Silver

W. G. Simon, S. T. Ahrens

The decay of highly excited nucleus, according to statistical theory, depends on the density of levels at the residual nucleus. If the angular momentum of the decaying nucleus is large, then the dependence of level densities on angular momentum as well as energy must be considered. According to the semi-classical theory of Ericson and Strutinsky¹ the level density can be written

$$\rho(U, J) = \frac{(2j+1)}{2(2\pi)^{\frac{1}{2}}} \frac{\rho(U)}{\sigma^3} e^{-\frac{j(j+1)}{2\sigma^2}}, \quad (1)$$

where $\rho(U)$ is the "ordinary level density for excitation U . The quantity σ is given by $\sigma^2 = IT/h^2$, with I the moment of inertia and T the nuclear temperature of the nucleus. We have made measurements of the energy and angular distributions of neutrons emitted from the interactions of 167 Mev O^{16} ions with Ag and

and Ni. These results are interpreted according to the statistical model of the nucleus using the above level density.

Neutrons were detected with the use of nuclear emulsions. These were placed at 15° intervals on a circle 8 inches from the targets which were bombarded at the Berkeley heavy ion accelerator by 160 Mev O^{16} ions. Proton recoils from elastic n,p collisions were used to detect neutrons. A new method for scanning the emulsions was used. We take advantage of the fact that the range and angle of a track, projected into the plane of the emulsion, are much easier to measure than the range and angle in space, and can be measured more accurately. The projected range of each track that makes a projected angle less than 30° with respect to the neutron direction is measured. We relate the distribution of these projected ranges $N(R_p)$ to the neutron energy spectrum through the relation

$$N(R_p) = \int_0^\infty N(E_n) g(E_n, R_p) dE_n, \quad (2)$$

where $g(E_n, R_p)$ is the probability that a neutron with energy E_n produces a proton with projected range R_p . The function $g(E_n, R_p)$ was determined and equation 2 solved numerically for each spectrum. For our purposes this method was more effective than "conventional methods."² A second method for emulsion scanning which used a digitized microscope was employed. Coordinates of the track are automatically recorded on IBM cards, and the energy of the neutron is computed directly. The approximate efficiencies (statistics acquired per unit scanning time) of the three methods were found to be 1:1.5:3 for the conventional, projected range, and digitized methods.

Preliminary results of these measurements are displayed in Figures 1-III and 2-III. The most striking feature of the center of mass distribution for nickel is the backward peaking. This is shown later to be a natural result of direct reactions.

Calculations for the spectra of emitted particles for multiple-particle emission with the level density equation 2 have been made by D. Reames.³ Reames employed for the following approximation in order to be able to cope with the difficulties

FIGURE I-III

FIGURE 2-III

arising from the multiple emission. A "first chance" emission spectra is calculated. Then an average residual nucleus is arrived at by averaging over the charge, mass, angular momentum, and energy of the residual nucleus. This procedure is continued until there is not enough energy to evaporate another particle. The results of these calculations are shown in Figures 1-III and 2-III. The normalization of these curves is arbitrary.

Our preliminary interpretation of the backward peaking in the case of nickel (and to a lesser extent also in the case of silver) is as follows: in a large fraction of heavy ion reactions, only a part of the incoming ion is captured by the target nucleus, the remainder of the ion continues on with velocity approximately equal to the initial velocity.^{4,5,6} Then, owing to the incomplete transfer of momentum, the excited residual nucleus is moving backward in the center of mass system. This results in a backward peaking of evaporated particles, especially the low energy ones. The nuclei having only part of the incident ion's momentum are less highly excited than the others. This further confines the peaking to low energies. The effect is smaller for silver because the residual nucleus in any case has only a small velocity. All of these effects are verified in Figures 1-III and 2-III. We intend to do calculations for the evaporation from target nuclei to which 1, 2, or 3 alpha particles have been transferred in an effort to decide more critically if the statistical model together with this incomplete momentum transfer mechanism can account for the observed spectra.

¹T. Ericson, *Advances in Physics* 9, 425 (1960).

²Louis Rosen, *Nucleonics*, Vol. 11, No. 8, p. 39 (1953).

³Donald V. Reames, *Phys. Rev.* B137, 332 (1965).

⁴Raymond Pfohl "Reactions Nucleaires Provoquees Les Interactions Du ²⁰Ne De 200 Mev Avec Les Noyaux De L'Emulsion Ionographique," De L'Universite De Strasbourg, thesis (Unpublished).

⁵W. J. Knox, A. R. Quinton, and C. E. Anderson, Phys. Rev. 120, 2120 (1960).

⁶J. T. Sikkeland, E. L. Haines, and V. E. Viola, Jr., Phys. Rev. 125, 1350 (1962).

IV. Emulsion Processing

W. G. Simon, S. T. Ahrens

We have developed the capability for processing thick nuclear emulsion plates at the University of Wyoming. A processing tank with a capacity for about 60 600 μ 1 x 3 emulsion plates has been fabricated. Processing solutions are temperature-controlled through use of a household refrigerator and stirred with water driven magnetic stirrers. We have processed 600 μ plates exposed to neutron sources to test our methods. It was found that Ilford type K-2 emulsions are not sensitive enough for our purposes even though in the past they have been. Apparently, the sensitivity of the manufactured plates has changed over the past few years. H. H. Heckman at the Lawrence Radiation Laboratory has come to the same conclusion. We are now experimenting with underdevelopment of the electron sensitive Ilford K-5 emulsions in order to obtain more satisfactory plates.

V. Neutron Spectrometer Simulation

H. B. Eldridge, D. L. Cunningham

As a means of studying the effects of parameter variation on the time-of-flight spectrometer, a computer program is being developed which simulates the life history of individual neutrons as they interact in the various components of the system. Several special techniques utilized in such a calculation are available in the literature,^{1,2} and adaption of many of them to the present system appears feasible. Also, this simulation will serve as a calculation of the efficiency of the spectrometer for the energies not available experimentally as discussed in the original proposal.

The general plan of the simulation program is to first consider a neutron source of arbitrary spatial and energy distribution from which particles are started from random space points into random directions but restricted to hit the first scintillator. Once a neutron has encountered the surface of the first scintillator, the mean free path is picked according to the well known total cross sections for n,p ³ and the various n,γ interactions⁴ for the material which composes the scintillator.⁵ The n,γ events are, of course, background; therefore, we also get an estimate of the signal to noise ratio insofar as γ background is concerned. When the neutron suffers an encounter inside the first scintillator, the type of encounter is chosen according to the relative cross sections for all possible types of encounters, and if the encounter is a n,p interaction, the scattering polar angle is picked from a distribution weighted according to the well known n,p differential cross section.⁶ The azimuthal angle is next picked from a uniform distribution.

The parameters chosen so far serve to determine the energies of the recoil proton and the energy and exit direction of the scattered neutron. This point of interaction in the first scintillator is then treated as a source for the second scintillator, and the neutron's subsequent history is followed in the same manner as outlined for the first scintillator. An event is considered a success if the neutron scatters from scintillator 1 and has an n,p interaction in scintillator 2 causing a recoil proton in the latter to acquire an energy above a prescribed bias. A failure, on the other hand, is a neutron, started from the source, that is not a success. The efficiency is consequently defined as the number of successful events divided by the total number of neutrons started from the source.

The parts of the program which pick from the different probability distributions for each physical process that can effect the life history of a neutron are, insofar as possible, written as independent subroutines so as to give them wider utility as well as to facilitate checking the program. It is also of interest to see how many neutron histories must be analyzed in order to

get a representative sample from the various distribution functions. To this end separate checks have been made on the various parts of the program to see how near the stochastic procedure reproduces the desired distribution function. Figures 1-V through 3-V are examples of such a calculation in which the geometry is as follows: a point monoenergetic source of neutrons is at $(-10, 0, 0)$ and a right circular cylinder (2 inches diameter by 2 inches long) of NE 102 plastic is centered at the origin with the z axis parallel to its longitudinal axis. In Figures 1-V through 3-V the frequency of occurrence for a particular value of the x , y , and z coordinates of the point which a neutron path intersects with the cylinder surface is plotted as a function of the coordinates for 10^5 neutrons emitted from the source. The frequency pattern for the x and y coordinates follow the outline of the cylinder in the x,y plane while the pattern of the z axis is uniform. This behavior is as expected from geometrical considerations.

Figure 4-V compares the analytic form of path length distribution of various energy neutrons in NE 102 plastic with the stochastically computed path length distribution.

Figure 5-V shows the stochastically computed efficiency of the first scintillator as a function of neutron energy with all other parameters fixed.

As a check on the simulation program a hand calculation of the spectrometer efficiency and energy resolution due to finite scintillator size has been made for various energy neutrons. In this calculation the total number of n,p collisions is computed per unit incident flux in scintillator 1 assuming the differential cross section is isotropic. The first scintillator is then treated as a point source and the number of n,p interactions in scintillator 2 due to this point source is computed. This number is plotted for several incident neutron energies as a function of the flight path (the distance between the scintillators) in Figure 6-V. Since the scintillators considered for the spectrometer are of finite size (the first is 2 inches in diameter by 2 inches long and the second is 5 inches in diameter by 5 inches long),

FIGURE 3-V

FIGURE 4-V

FIGURE 5-V

FIGURE 6-V

NEUTRON SPECTROMETER EFFICIENCY

SCINTILLATOR 1 2" Dia x 2" NE102

SCINTILLATOR 2 5" Dia x 5" NE102

there will be a finite angular acceptance for the n,p interactions in the first scintillator by the second scintillator. The energy of the scattered neutron is related to the energy of the incident neutron through the scattering angle; therefore, the finite size of the scintillators leads to a limitation in the energy resolution of the spectrometer. The percentage energy spread due to finite scintillator size (which is independent of energy) is plotted as a function of flight path in Figure 7-V. From the Figures 6-V and 7-V one sees that a reasonable compromise may be made between energy resolution and efficiency.

¹J. B. Marion and J. L. Fowler, Fast Neutron Physics Part I (Interscience Publishers, Inc., New York, 1960) pp. 929.

²D. Cashwell and C. J. Everett, A Practical Manual on the Monte Carlo Method for Random Walk Problems, LASL Report 2120, 1967.

³J. B. Marion and J. L. Fowler, Fast Neutron Physics Part II (Interscience Publishers, Inc., New York, 1960) pp. 2185.

⁴M. D. Goldberg, et al., Neutron Cross Sections, Brookhaven National Laboratory Report, TID-4500, (1966).

⁵Nuclear Enterprises, LTD, Winnipeg, Canada.

⁶J. B. Marion and J. L. Fowler, Fast Neutron Physics Part II (Interscience Publishers, Inc., New York, 1960) pp. 2185.

VI. Neutron Spectrometer Construction

H. B. Eldridge, R. J. Jiacoletti, J. A. Shideler

A new type of neutron spectrometer has been constructed and is at present being tested at the University of Wyoming. The spectrometer consists of two NE 102 right circular cylinders each viewed by separate photomultiplier tubes, conventional electronics for measuring the time interval between two electrical pulses, and a pulse height analyzer. The principle upon which the spectrometer works is quite simple and may be described as follows.

FIGURE 7-V

NEUTRON SPECTROMETER RESOLUTION

Scintillator 1 2" Dia x 2" NE102

Scintillator 2 5" Dia x 5" NE102

RESOLUTION ($\times 10^{-2}$)

FLIGHT PATH (METERS)

Neutrons with an arbitrary energy distribution are incident upon a right circular section of fast plastic (NE 102) of 2 inch diameter by 2 inches long which is viewed by a very fast, high gain photomultiplier tube (Amprax 56 AVP). A second right circular section of fast plastic scintillator (NE 102) of 5 inches in diameter by 5 inches long also viewed by a photomultiplier tube (58 AVP) is placed a fixed distance from the first scintillator. Recoil proton pulses in the first scintillator serve as start pulses while the recoil protons in the second scintillator serve as stop pulses for the conversion of the time interval into a pulse height. This pulse height distribution is then stored in a conventional pulse height analyzer. A knowledge of the composition of the plastic scintillator, the n,p cross section as a function of energy, the scattering angle (45°), and the flight path then allow a measure of the absolute neutron flux as a function of energy onto the first scintillator.

As a means of studying the resolution of the instrument experimentally, a series of measurements are in progress whereby the n, γ spectrum is being measured for a Pu-Be source. An example of a typical spectrum is shown in Figure 1-VI where time is inverted so that the γ peak is the peak at the right while part of the neutron spectrum shows up as the rather broad peak at the left; the spread of the γ peak is, of course, a measure of the instrumental resolution. The width of the γ peak in Figure 1-VI corresponds to a full width at half maximum of 2×10^{-9} seconds. The antisymmetric shape of the γ peak has been traced to pileup in our rather slow analog to digital converter which requires rather long pulses. Additional work is under way to limit the count rate to the analog to digital converter using a pair of fast discriminators followed by a fast coincidence unit.

A program is being written to transform the time spectra, such as Figure 1-VI, into energy spectra. Such a transformation will include folding in of the time calibration of the system as well as the n,p cross section. The rate of data accumulation

FIGURE I- VI

Partial Time Spectrum

Pu Be Neutron Source

Scintillator *1 2"X2" NE 102

Scintillator *2 5"X 5" NE 102

512 Channel Full Scale

Counts

6000
5000
4000
3000
2000
1000
0

Neutron

Gamma

160

200

250

300

350

Channel Number

and analysis is presently governed by the fact that the punched paper tape which is our present output medium is very awkward input medium for the University Computing Center.

VII. Measurement of the Energy Spectrum of Neutrons from Neutron Sources

W. G. Simon

In performing these measurements we have used essentially the same procedures we intend to use in measuring neutron spectra produced at the Boulder Cyclotron; thus, these measurements serve as an operational test for the proposed method. Also, new measurements of these spectra are desired in order to have a better basis for determining experimentally the dependence of the efficiency of the scintillation spectrometer on neutron energy.

Emulsions were exposed at distances of 2.5 inches and 5 inches from a Pu-Be source yielding 1.6×10^6 neutrons/sec, and at a distance of 4 inches to a Ra-Be source yielding 1.58×10^5 neutrons/sec. It was necessary to use lead shielding between the source and detectors for the Ra-Be source, owing to the large flux of γ rays emitted. The emulsions were scanned with the aid of a digital readout microscope. The scanning procedure is as follows. The coordinates of each "qualified" proton recoil from n,p collisions in the emulsion are recorded at intervals along the track spaced so that an adequate reconstruction of the track can be made. A "qualified" proton recoil is one that (a) begins within an area delineated by an eyepiece reticle, (b) ends within the emulsion, and (c) makes an angle projected into the plane of the emulsion, of less than 45° with respect to the initial direction of the neutron.

A computer program, written for use in the Boulder Cyclotron experiments, was used to analyze the spectra. This program (a) calculates the range energy and orientation of each track, (b) rejects those tracks with dip angles greater than 45° (This procedure is too tedious to be done by the scanner at the time

FIGURE I-VII

FIGURE 2-VII

scanning is done.), (c) calculates the neutron energy and sums the results into neutron spectra.

The results are shown in Figures 1-VII and 2-Vii and are then compared with the experimental results of L. Stewart et al.¹ and with calculations by Hess, et al.²

¹Leona Stewart, Phys. Rev. 98, 740 (1955).

²N. N. Hess, Ann. Phys. 6, 115 (1959).

VIII. Personnel

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