Neutron-Proton Scattering in the Energy Range of 18 to 21 Mev*

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The relative cross sections for neutron-proton scattering in the neutron energy range of 18 to 21 Mev were measured by means of a proportional counter telescope at the laboratory proton recoil angles of 15 degrees and 44 degrees 24 minutes, respectively. From these data a ratio of 1.06 ± 0.16 for neutrons scattered in the center-of-mass system in the backward direction to those scattered in the sideways direction was computed.

INTRODUCTION

NEUTRON–PROTON scattering experiments carried out in the neutron energy range of 10 to 30 Mev include those of Fowler[1] at 27 Mev and a set of experiments in the vicinity of 12 to 15 Mev by various investigators.[2–4] The results of all the experiments in the range of 12 to 15 Mev, with the exception of the experiments by Amaldi, indicated isotropic, or nearly isotropic scattering. The results of Amaldi indicated a high anisotropy in favor of neutrons scattered in the sideways direction in the center-of-mass system. At 27 Mev Fowler found an anisotropy in favor of the neutrons scattered in the backward direction.

It was the purpose of this experiment to contribute data in the neutron energy interval between 18 and 21 Mev. In this experiment the detection of recoil protons, scattered by neutrons, from a polyethylene foil was accomplished by use of a proportional counter telescope which selected protons in a given energy range and in a given direction.

The telescope consisted of an array of four cylindrical proportional counters (see Fig. 1). Lead sleeves of $\frac{1}{8}$-inch wall thickness were inserted in the brass counters to stop protons produced in the brass walls. Lead was used because of its very low (n,p) cross section.[5] The central wire of each counter was made of 0.0032-inch nickel, which was shielded at each end by 0.06-inch Inconel tubing to keep the sensitive region of the counter confined to the central portion.

An evacuated fore-chamber was constructed in front of the counter telescope and separated from it by a 0.003-inch Al partition. The front end of this fore-chamber was sealed by 0.006-inch Al foil in front of which was placed the scattering foil. The dimensions of the forechamber were such as to place the scattering foil at the position required by the geometry of the counter telescope.

The output of each counter was fed successively through a preamplifier, linear amplifier, coincidence analyzer channel, scaler, and mechanical recorder. The mixing of all four channels and the selection of coincidence and anticoincidence pulses was done in the coincidence analyzer. The triple coincidence and anticoincidence outputs were each fed to a scaler and mechanical recorder.

The output of a parallel plate thorium fission neutron monitor[6] was likewise fed through a preamplifier, linear amplifier, scaler, and mechanical recorder. The selection of pulse height was done by a discriminator incorporated in the scaler circuit.

The source of high energy neutrons was the University of Pittsburgh cyclotron. This is a conventional cyclotron of 47-inch pole diameter. For this problem, neutrons were obtained from the (α,n) reaction with an alpha-beam and a beryllium target. The cyclotron was capable of giving alpha-particles an energy of approximately 30 Mev, and with the positive Q of 6 Mev for $Be^9(\alpha,n)C^{12}$ the resulting neutron energy spectrum extended to approximately 36 Mev.

Data was taken at the proton recoil angles of 15 degrees and 44 degrees 24 minutes, measured in the laboratory system. For these runs the counter system was filled with a mixture of argon and 3 percent carbon dioxide at a pressure of 20 cm of mercury. A counter

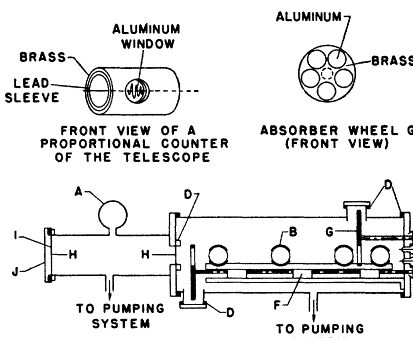

FIG. 1. Schematic diagram of the counter telescope. A—mechanical vacuum gauge, B—proportional counter, C—Wilson seals, D—rubber gaskets, E—Stupakoff seals, F—Lucite block, G—absorber wheel, H—aluminum foil, I—polyethylene foil, J—lead foil.

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[1] Brolley, Coon, and Fowler, Phys. Rev. **79**, 227 (1950).

[2] Amaldi, Bocciarelli, Foretti, and Trabacch, Naturwiss. **30**, 582 (1942).

[3] C. F. Powell and G. P. S. Occhidini, *Fundamental Particles* (The Physical Society, London, 1947), p. 150.

[4] J. S. Laughlin and P. G. Kruger, Phys. Rev. **73**, 197 (1948).

[5] B. Cohen, "Nuclear reactions," thesis, Carnegie Institute of Technology (1950) (to be published).

[6] B. Rossi and H. Staub, *Ionization Chambers and Counters* (McGraw-Hill Book Company, Inc., New York, 1949), p. 207.

voltage of approximately 840 volts was found satisfactory for operation of the counters in the proportional range.

PRELIMINARY TESTS AND CALIBRATION

In order to check the functioning of the electronic gear before and after each run, a signal from a pulse generator was fed into the input circuits of the preamplifiers. This pulse was a negative square pulse of approximately 2 microseconds duration, and approximated in shape the proton pulses fed from the proportional counters.

By allowing this pulse generator to trigger the electronic system it was possible to check the behavior of

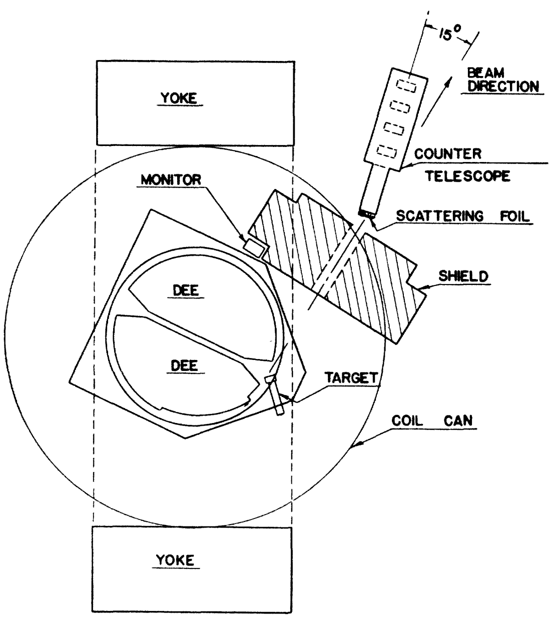

FIG. 2. Cyclotron and counter telescope.

all amplifier channels, the mixing circuit, and the scalers.

Using a Tektronix oscilloscope Model 511 it was possible to measure and record the outputs of the linear amplifier channels fed by the pulse generator. This afforded a check on the gains of the amplifiers from time to time.

As a check on the behavior of the proportional counters, polonium alpha-sources were placed on the absorber wheels. These alpha-sources could be placed in front of counters Nos. 1, 3, and 4. By measuring the amplitude and duration of the linear amplifier output pulses it was possible to judge the condition of the counter gas filling. This alpha-pulse measurement was an added check on the electronic system. Also by measuring the amplitude of these output pulses, and knowing the alpha-energy loss in the counter, the discriminator bias of the coincidence analyzer could be set to count pulses produced by protons up to a certain maximum energy.

Owing to the finite length of time required for the collection of the ions in the proportional counters, it was necessary to adjust the gate widths of the univibrator in each of the four analyzer channels to the following values: 2.0 microseconds for channels Nos. 1, 2, 3 and 6.0 microseconds for channel No. 4. Also a delay of 2.2 microseconds was introduced between the coincidence output and the anticoincidence input.

In order to position the telescope for the experiment it was necessary to know accurately the position of the cyclotron target. To take advantage of the maximum beam intensity it was necessary to know the horizontal angular distribution of the neutron beam.

An angular distribution of the neutron beam, obtained from the reaction $Be^9(\alpha,n)C^{12}$, was taken with silver threshold detectors placed a few inches apart on a horizontal circle of 75-cm radius centered at the target. This distribution, like some of those encountered by Falk,[7] had two maxima about 27 degrees apart. The maximum farther from the cyclotron yoke was chosen for the scattering experiment.

An accurate survey of the cyclotron target was made after the removal of one of the side plates from the cyclotron vacuum chamber. A horizontal axis, passing through the target at a point where the internal beam strikes the target cup, and passing through the neutron beam maximum, was taken as the reference line. The vertical projection of this axis was marked on the cyclotron coil can and on the floor.

The counter telescope was orientated with respect to this horizontal axis, and pivoted at a point 125 cm from the cyclotron target about a vertical axis passing through the center of the scattering foil. The scattering angles were marked on the floor of the cyclotron room, and the telescope was positioned by means of plumb bob and ruler. The error in angular location of the telescope was less than $\frac{1}{4}$ degree.

To avoid blocking the individual proportional counters by an excessive number of proton pulses, and to avoid a high accidental triple coincidence rate, it was necessary to shield the counter system from the direct neutron beam. This was accomplished by building a cement shield 2 feet thick and 4 feet wide between the counter telescope and the cyclotron target. This shield was constructed from cement blocks of 4 inches$\times$8 inches$\times$16 inches dimensions. The shield was built on the lower cyclotron coil can and extended to the lower surface of the upper coil can. An aperture of 4 inches $\times$5 inches through the shield allowed the neutron beam from the cyclotron target to strike the surface of the scattering foil (see Fig. 2). This shield was effective in reducing the individual counter rates by a factor of 10 over that obtained without a shield.

To prevent those protons produced in the shield from entering the telescope, a lead foil of approximately $\frac{1}{16}$-inch thickness was placed directly in front of the

[7] C. Falk, Phys. Rev. 83, 499 (1951).

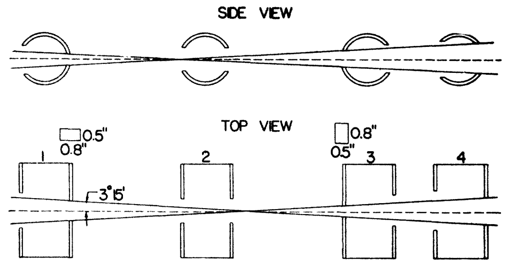

FIG. 3. Counter aperture geometry.

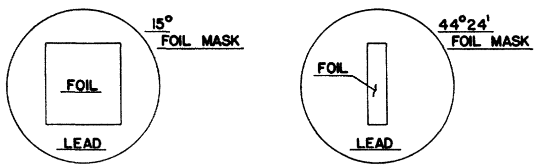

FIG. 4. Lead mask apertures for scattering foils.

scattering foil. Lead was used because of its low (n,p) cross section.[5]

EXPERIMENTAL PROCEDURE

In order to select the recoil protons scattered at a given angle by neutrons in the energy range of 18 to 21 Mev from those scattered by the rest of the neutron spectrum, two sets of proton energy absorbers were required. One set was located in front of counter No. 1, and the other set between counters Nos. 3 and 4.

The Al absorber thickness for the front set was chosen so that protons produced by 18-Mev neutrons on the inside (telescope side) of the polyethylene, and traveling normal to that surface, would enter counter No. 3 with an energy of approximately 0.2 Mev. The thickness of the rear Al absorber set was adjusted so that protons produced by 21-Mev neutrons on the outside surface (target side) of the polyethylene, and traveling normal to that surface, would just enter counter No. 4 with less than 0.1 Mev.

To calculate the thickness of the Al absorbers, the energy loss in the counter gas and the energy loss in the polyethylene scatterer, it was necessary to have an accurate set of range energy curves. The curves used for aluminum and argon were taken from the compilation of range-energy curves published in 1949 by the University of California Radiation Laboratory, Berkeley, California.[8] The calculations of Hirschfelder and Magee[9] were used for polyethylene.

Different thicknesses of polyethylene foil were required for different scattering angles in order to choose identical segments of the neutron spectrum. The thickness of the polyethylene was chosen so that those protons produced on the outside surface of the foil by neutrons of a predetermined energy, and traveling along a normal through the foil, would lose sufficient energy to emerge from the inside surface with the minimum proton energy, i.e., the energy of a proton produced on the inside surface by an 18-Mev neutron. At the proton recoil angle of zero degrees this predetermined neutron energy chosen to produce the above mentioned protons was 19.60 Mev. For all other angles the proton energy was given by $E_p = E_n \cos^2\theta$, where E_p equals the proton energy in Mev, E_n equals the neutron energy in Mev, and θ was the proton recoil angle in the laboratory system.

At the proton recoil angles of 15 degrees and 44 degrees 24 minutes the polyethylene thicknesses were 53.27 mg/cm^2 and 15.27 mg/cm^2, respectively.

Protons leaving the foil at angles of several degrees with the normal can be detected by the counter system. This small angular spread produced a corresponding spread in the neutron energy interval and, owing to the $\cos^2\theta$ relation, this energy spread became greater with increasing proton recoil angle. In order to match as closely as possible neutron energy spectra at various proton recoil angles it was necessary to construct the defining counter apertures (rear aperture No. 1, front aperture counter No. 3) as rectangular slits, and to introduce a third set of apertures directly behind the scattering foil (see Figs. 3 and 4). This third set of apertures was cut from $\frac{1}{8}$-inch lead plate and was designed to constrict the angular spread at the two recoil proton angles, chosen for the experiment, to values which gave approximately the same spread in the neutron energy interval.

Making use of the polyethylene range-energy curves, the $E_p = E_n \cos^2\theta$ relation, and the counter aperture

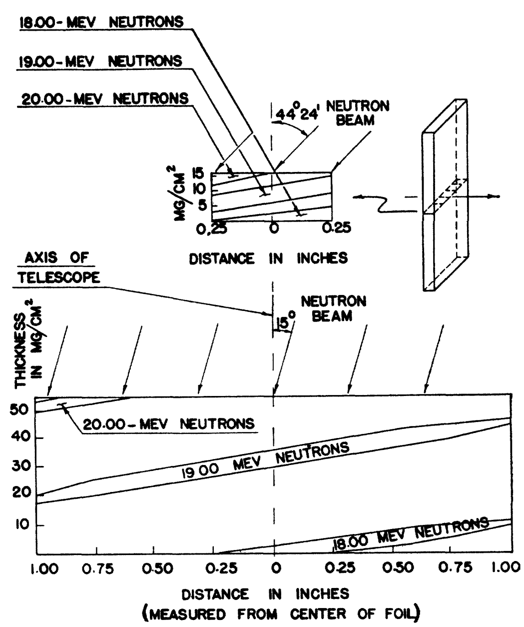

FIG. 5. Distribution in scattering foil of these neutrons which produce protons emerging from scattering foil with minimum proton energy.

[8] Aron, Hoffman, and Williams, UCRL-121, second revision (1949).

[9] J. Hirschfelder and J. Magee, Phys. Rev. 73, 207 (1948).

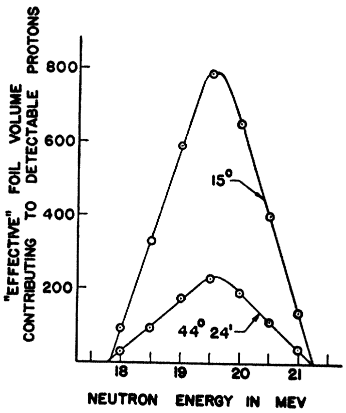

FIG. 6. "Effective" scattering foil volume *versus* neutron energy.

geometry, it was possible to trace the volume of scattering foil contributing to those protons which emerged from the inside scattering surface with a given energy and which were produced by neutrons of a given energy. The volume of such a portion of the foil was equal to the cross-sectional area which was effective for neutrons of that given energy, times the vertical height of the foil modified by the vertical aperture contributions. Furthermore, since both foils had the same vertical height and the same vertical aperture dependence, it was sufficient for any comparison to plot only the cross-sectional areas of the scattering foil contributing to the above mentioned protons (see Fig. 5). Such calculations and graphs were compiled for the scattering foils used at the angles of 15 degrees and 44 degrees 24 minutes.

By measuring the areas enclosed for a given neutron energy responsible for protons in the detectable range it was possible to plot the effective cross-sectional areas as a function of neutron energy (see Fig. 6).

A neutron energy spectrum was measured for the (α,n) reaction of the cyclotron alpha-particles on a beryllium target. The neutron intensity was measured at several neutron energies in the energy range of approximately 9 to 21 Mev by means of the counter telescope. This spectrum checked very well with the predictions of Cohen.[5] The spectrum is plotted in Fig. 7.

Using the neutron energy spectrum it was possible to weight the contributions of the two scattering foils for the proton recoil angles of 15 degrees and 44 degrees 24 minutes. By multiplying the effective cross-sectional area (proportional to foil volume) *versus* neutron energy curve by its respective neutron spectrum weight, it was possible to get the "effective" volume of scattering foil at the two angles, and hence the ratio between them (see Fig. 8).

In order to determine the background, contributed by the (n,p) reaction in the carbon atoms in the polyethylene foil, a carbon foil of equivalent stopping power was deposited on a lead foil of $\frac{1}{16}$-inch thickness. When the polyethylene foil was removed for a background count, it was replaced by this lead-carbon foil. It was found, however, that to within the few percent error in this measurement it was not possible to detect the difference between the background with the above lead-carbon foil in place or with just a blank lead foil in place. Hence, the scattering contribution of the protons in the polyethylene foil was determined by subtracting the counting rate with the above lead-carbon foil present from the counting rate with the polyethylene foil in place.

DISCUSSION OF RESULTS

The ratio between the neutron-proton scattering cross section at a neutron scattering angle of θ_1 degrees from scattering foil No. 1 and the neutron-proton scattering cross section at a neutron scattering angle of θ_2 from scattering foil No. 2, both angles measured in the center-of-mass system, is given by

$$R=\frac{\sigma(\theta_1)}{\sigma(\theta_2)}=\frac{N_1}{N_2}\cdot\frac{d\Omega_2'}{d\Omega_1'}\cdot\frac{\text{effective } f_2}{\text{effective } f_1},$$

where N_1 and N_2 are the number (normalized to the monitor) of protons scattered at the angles of $(180-\theta_1)$ and $(180-\theta_2)$ degrees, respectively; $d\Omega_1'$ and $d\Omega_2'$ are the elements of scattering solid angles in the center-of-mass system into which these recoil protons are scattered; and effective f_1 and effective f_2 are proportional to the "effective" number of target nuclei presented by the foils No. 1 and No. 2.

The ratio N_1/N_2 comes directly from the experimental data and has a value of 6.5 ± 1.0. This value is

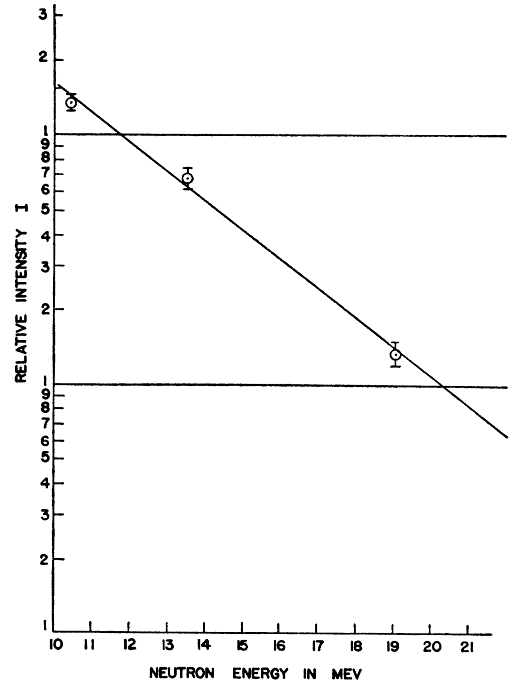

FIG. 7. Neutron energy spectrum from Be(α,n) reaction.

obtained from six separate sets of runs, using

$$\frac{N_1}{N_2}=\frac{\sum[(N_1/N_2)_i/e_i]}{\sum(1/e_i)}\pm\frac{\sqrt{n}}{\sum(1/e_i)}=6.5\pm1.0,$$

where e_i is the probable error in the ith ratio, $(N_1/N_2)_i$, and n is the number of sets.

From the relation $d\Omega'_{\text{cm}}=4\cos\theta d\Omega_{\text{lab}}$ between an element of solid angle in the laboratory system and an element of solid angle in the center-of-mass system, we have $d\Omega_2'/d\Omega_1'=0.547$.

The ratio of the "effective" volume of scattering foil for a proton scattering angle of 15 degrees to the "effective" volume of scattering foil for a proton scattering angle of 44 degrees 24 minutes is equivalent to the ratio of the areas under the neutron-spectrum weighted curves shown in Fig. 8. This ratio has a value of 0.298±0.10.

Hence, the product of these three factors is

$$R=1.06\pm0.16.$$

The results of this experiment seem to be consistent with the existing data, provided that the results of Amaldi are discounted in favor of the predominance of corresponding data presented by numerous other investigators. That is, there does not appear to be any high degree of anisotropy in the neutron-proton scattering at this energy range.

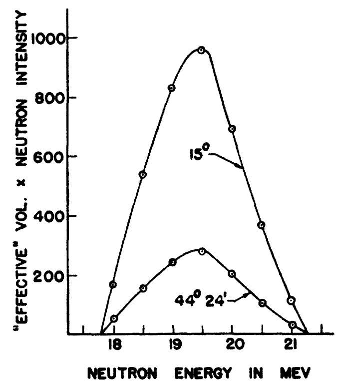

FIG. 8. Spectrum-weighted neutron energy intervals.

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(d,n) Reactions with 15-Mev Deuterons. Part I. Angular Distributions*†

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Nine elements are bombarded with 15-Mev deuterons from a cyclotron. The resulting angular distributions of 9.25- to 13.1-Mev neutrons are measured by means of a four-proportional counter telescope and also by threshold detectors. It is observed that all the measured angular distributions are peaked in the forward direction, some showing a peak at 0° and others peaks at 10°–15° with respect to the deuteron beam. Different methods of production of neutrons from *(d,n)* reactions are discussed, and it is shown that most of the observed neutrons are produced by a stripping process.

INTRODUCTION

ALTHOUGH the interaction between high energy deuterons (~200 Mev) and nuclei has been thoroughly investigated and explained,[1–3] the nature of the interaction at medium deuteron energies is not clear. Several investigations[4–7] have not produced sufficient evidence to determine whether stripping,[2] which explained the high energy reaction, can account for the nature of the yields in *d,n* and *d,p* reactions.

The deuteron beam of the University of Pittsburgh cyclotron was used to investigate the characteristics of the yields of *(d,n)* reactions. These experiments can be divided into two groups: the investigation of the angular distributions of neutrons produced by 15-Mev deuterons, which is reported here, and the study of neutron energy spectra and neutron yields from *d,n* reactions, which will be reported in Part II. The integrated interpretation of all the data will be pre-

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