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Neutron-Proton Scattering at 27 Mev*

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Monoenergetic neutrons of energy 27.2 Mev were produced by 10-Mev deuterons incident on a gaseous tritium target. Protons recoiling from the neutrons were observed in a fourfold coincidence proportional counter telescope. The angular distribution of neutrons scattered through angles in the range from 180° to 76° in the CM system was measured. The observed ratio of scattering at 180° to that at 90° was 1.28±0.10.

I. INTRODUCTION

It is thought that experimental study of the scattering of neutrons by protons will yield fruitful information about the nature of nuclear forces. For neutrons having an energy of 14 Mev or less, measurements[1,2] indicate that the scattering is isotropic in the center-of-mass system, though the accuracy of the experiments does not preclude the possibility of there being a 5 percent anisotropy. For 40- and 90-Mev neutrons, however, the experiments indicate a definite anisotropy with a minimum in the intensity of scattering at 90° and approximate symmetry around 90° over the angular region investigated.[3,4] In the present experiment, the scattering of 27.2-Mev neutrons has been studied by observation of the recoil protons emerging from a hydrogenous radiator into a fourfold coincidence counter telescope. A preliminary report of the results of this investigation has been given previously.[5]

II. EXPERIMENT

For the present measurements neutrons were produced by the reaction

$$D+T^3=\mathrm{He}^4+n+17.6\ \mathrm{Mev}.$$

Deuterons, accelerated by the cyclotron, entered a tritium-filled gas target cell (Fig. 1), and the neutrons emitted in the forward direction were used. The cyclotron beam was brought to a focus by a wedge-shaped magnet and limited by a series of circular apertures to an angular divergence of ±0.5°. The region in which the experiment was performed was 15 feet from the cyclotron exit port and was shielded from the cyclotron by a wall of water and paraffin three feet thick.[6] After passing through a 0.952-cm diameter hole in a gold diaphragm, the beam entered the target cell through a dural window of thickness 15.6 mg/cm². The gas cell was filled to a pressure of 4.2 atmos with a mixture of 83 percent tritium and 17 percent hydrogen gas. After passing through the target gas, the beam was stopped by a gold disk to minimize neutron background. Accurate alignment of the axis of the gas cell with the direction of the beam was accomplished by use of a similar cell with a transparent end, so that the position of the beam could be determined by burning photographic film. Relative neutron yield was monitored by integrating the deuteron beam current (0.2 to 1 μamp). Handling of the tritium gas was facilitated by using a small stainless steel vessel containing uranium, in which the tritium was absorbed whenever it was desirable to empty the target cell. Tritium was evolved from the uranium by heating.

Prior to the installation of the gas target, the energy of the cyclotron beam was measured to be 11.0±0.2 Mev by deflection in a magnetic field.[6] During the course of the experiment the energy of the neutrons produced both by the *D-D* reaction and the *D-T* reaction was measured by determining aluminum absorption curves for the recoil protons. The results of these measurements agreed with the conclusion that the incident deuteron energy was 11.0 Mev within the precision of the data (about 4 percent).

Principally because of the loss of energy of the deuterons in passing through the tritium gas, the neutrons were not strictly monoenergetic. After penetrating the dural window, the deuterons had an energy of 10.1 Mev. The average deuteron energy in the tritium target was 9.76 Mev, with a maximum spread in energy of about 0.8 Mev. If one uses 17.6 Mev for the reaction energy, it follows that the energy of the 0° neutrons from the *D-T* reaction was 27.2±0.6 Mev, where the ±0.6 Mev includes the effect of the uncertainty in deuteron energy, and the neutron energy spread resulting from target thickness.

The proportional counter telescope and recording system was a modification of the type used for the determination of the angular distribution of 14-Mev neutrons scattered by protons.[2] Proton recoils were produced in polyethylene foils mounted in the counter telescope shown in Fig. 1. These foils had a total thickness of 45.9 mg/cm² and an exposed diameter of 1.613 cm. The recoil protons passed through four platinum-lined proportional counters. At the end of the third counter the recoil protons passed through a 7 mg/cm² Dural window into a 3.0-cm air gap in which could be inserted

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aluminum absorbers, and then through a second 7 mg/cm^2 Dural window into the fourth proportional counter. For each angular setting of the counter telescope a thickness of aluminum absorber was used (column 2, Table II) such that the lowest energy recoil proton had sufficient residual range to pass through the fourth counter. The purpose of the aluminum absorbers was to reduce the number of background coincidence counts and to increase the height of pulses originating in the fourth counter. In choosing the aluminum absorber thickness, allowance was made for errors in determining proton energy and for straggling in range. The counters were filled with 0.40 atmos argon containing approximately 2 percent CO_2. Ionization pulses produced in the counters were amplified by Los Alamos Model 500 amplifiers with a rise time of about 0.1 μsec and RC clipping time constant of 0.2 μsec. The amplifiers drove discriminators, from which the pulses were fed into a coincidence circuit which recorded coincidences between the first three channels as well as coincidences between all four channels. Each discriminator also drove a scaler to ascertain the number of counts in each channel. To facilitate background determinations the platinum holder which held the polyethylene foil could be rotated to expose the back side, on which was mounted a disk of graphite containing the same amount of carbon as was contained in the polyethylene radiator.

Since the energy loss of the recoil protons in a single counter was in some instances only 40 kev, special care was required to ascertain at what level the pulse-height discriminators should be set. A preliminary set of measurements was made to determine the dependence of coincidence counting rate on the bias setting in each channel. To obtain these bias curves, all the biases were set (by trial and error) sufficiently low to detect recoil protons, and the number of quadruple coincidence counts per μcoulomb of beam charge was observed as a function of bias setting in one channel. This procedure was repeated for each of the four channels, and was done with the counter telescope set to receive protons recoiling at 0° and at 45°. The subsequent operating bias setting for each channel was selected to be approximately 25 percent below the end of the bias curve plateau. For taking data at intermediate angles, the operating biases were selected by means of a linear interpolation between the values determined for 0° and 45°. For 52° the same settings were used as for 45°. In order to reproduce bias settings from day to day, a small gamma-ray source was placed next to a counter in a reproducible position, and the counting rate used as an indication of a change in bias.

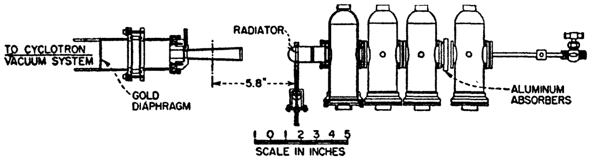

FIG. 1. Target and fourfold coincidence counter telescope. The tritium target cell is shown attached to the port through which the deuteron beam emerges. The polyethylene radiator in the counter telescope receives neutrons emerging from the target in the forward direction.

Two series of neutron-proton scattering measurements were made: one with the center of the polyethylene radiator at a distance of 14.7 cm from the center of the tritium target ("near geometry"), and the other in which the radiator was 38.8 cm from the center of the tritium target ("far geometry"). To detect protons at different angles, the counter telescope was mounted to rotate about a vertical axis through the polyethylene foil. The plane of the foil was maintained perpendicular to the axis of the telescope. During the first series of runs ("near geometry"), proton recoils were counted at angles of 0, 15, 30, and 45 degrees in the laboratory system. In the second series of runs ("far geometry"), measurements were made at 0, 15, 30, 37.5, 45 and 52 degrees. For a given angular setting, the coincidence count per μcoulomb of deuteron current was determined for a variety of conditions as tabulated in Table I. As is indicated in this table, run (a) measured the number R_T, of proton recoils produced in the polyethylene radiator by the D–T neutrons, together with certain background effects which could be evaluated from runs (b), (c), (d), and (e). The aluminum absorber used in run (b) was sufficient to absorb all protons, whether recoiling from neutrons or originating from (n,p) disintegrations. Therefore, the counts observed in run (b) were due to accidental coincidences between triple coincidence counts (real or accidental) in the first three counters and single pulses in the fourth counter. The resolving time (approximately 0.5 μsec) calculated from the observed number of accidentals was used to calculate the number of accidental coincidences to be subtracted as background from runs (a), (c), (d), and (e). The results of run (e) indicated that in every case D_H was a negligible background of less than one-half percent. By reference to Table I, one can conclude therefore that the desired quantity R_T is obtained by a subtraction of the sum of runs (c) and (d) from run (a). The magnitude of these background corrections

TABLE I. Operating conditions under which coincidence counts were recorded.

Run type	Target	Radiator	Aluminum absorber	Number of coincidence counts of specified origin[a]
(a)	T	CH_2	see Table II	$R_T+R_H+D_T+D_H$
(b)	T	CH_2	1.10 g/cm^2	only accidentals
(c)	T	C	see Table II	D_T+D_H
(d)	H	CH_2	see Table II	R_H+D_H
(e)	H	C	see Table II	D_H

[a] R_T = number of protons recoiling from D–T neutrons and originating in the CH_2.
D_T = number of disintegration protons arising from (n,p) reactions induced by D–T neutrons.
R_H = number of protons recoiling from background neutrons and originating in the CH_2.
D_H = number of disintegration protons arising from (n,p) reactions induced by background neutrons.

TABLE II. Angular distribution data and average corrections.

		Percentage correction applied to uncorrected values				Corrected number of quadruples per microcoulomb	
Lab angle for recoil proton (1)	Thickness of Al absorber including windows g/cm^2 (2)	Average for accidental coincidences, run (b) (3)	Average for counting losses (4)	Background D_T, from run (c) (5)	Background R_H, from run (d) (6)	Un-normalized data (7)	Near geometry normalized to far geometry (8)
Near geometry							
0°	0.70	−9.6	+38.4	0	0	4.03±0.13	0.517±0.017
15°	0.43	−5.5	+25.0	0	0	3.95±0.10	0.507±0.013
30°	0.18	−6.4	+14.2	−9.0	−4.7	3.14±0.10	0.403±0.013
45°	0.027	−1.6	+7.9	−17.2	−18.4	2.24±0.08	0.287±0.010
Far geometry							
0°	0.70	−6.5	+16.7	0	−1.1	0.516±0.017	
15°	0.43	−6.0	+11.2	−1.7	−1.3	0.469±0.019	
30°	0.25	−3.8	+7.4	−6.1	−4.0	0.383±0.017	
37.5°	0.15	−2.5	+7.6	−12.5	−4.8	0.341±0.020	
45°	0.055	−0.6	+2.6	−17.3	−9.9	0.273±0.020	
45° (0° bias)	0.055	−2.5	+11.7	−17.0	−12.1	0.276±0.034	
52°	0.014	−0.4	+2.9	−18.6	−17.4	0.246±0.015	

is given in Table II, columns 3, 5, and 6. The tabulated number is an average of the corrections applied to individual runs and represents the average percentage of the uncorrected value applied.as correction.

Counting losses occurred because of the short but finite recovery time of the pulse shaping circuits and because of the high counting rate which in some cases was as high as 2×10^4 per sec per channel. The background pulses were due to argon recoils from the *D–T* neutrons, argon recoils from background neutrons, gamma-rays, etc. To make it possible to correct for losses, "near geometry" data were taken with various values of cyclotron beam current. The true coincidence count Q, which would occur in the absence of losses, is related to the observed coincidence count Q', by the formula

$$Q=Q'/(1-\tau\Sigma),$$

where τ is the average recovery time and Σ is the sum of the counting rates in the four channels. According to this relation a plot of Q' *versus* Σ will yield a straight line with $Q'=Q$ at $\Sigma=0$. "Near geometry" data were plotted in this way and a graphical extrapolation made to determine the corrected coincidence count.

When a complete set of data at the "near geometry" position had been obtained, the counters were moved to the "far geometry" position to improve the angular resolution and also to increase the angular range over which measurements could be made. Correction of "far geometry" data for the relatively small counting losses was done by extrapolation to zero counting rate with the same slope as determined from the "near geometry" data. The average counting loss corrections are listed in Table II, column 4. Because of variation in beam current, corrections for counting losses as well as corrections for accidental coincidences varied by a factor of three for different runs. After these corrections were applied, however, data taken at different times were consistent within the standard deviation expected to arise from the statistics of counting, from random errors in beam measurement, and from fluctuations of the number of target atoms in the gas cell which was frequently emptied and refilled.

It seemed advisable to check on the possibility of systematic error being introduced by the method of bias setting, since the biases were changed with angle in a systematic way in order to minimize backgrounds. For this reason data were taken at 45° with the bias settings normally used for 0° runs. As is indicated in Table II, the data taken in this fashion agreed quite well with the data taken using normal biases. This result also furnished evidence that the counting loss corrections were applied correctly, since the counting loss for the lower bias settings was 4.5 times that for the higher bias settings.

To avoid the possibility of the data being affected by long time drifts in the characteristics of the apparaus, relatively short runs (long enough to obtain about 100 quadruple coincidence counts) were taken at a given angular setting, whence the angle was changed to a new value selected at random. This procedure was continued until about 1000 counts were accumulated at each angle. When the final data were assembled for this series of runs, which occurred over a period of six weeks, no systematic trend of the values for a given angular setting could be discerned. The results of separate runs at a given angle varied around their mean in approximately a gaussian distribution. The standard errors were slightly larger than the statistical errors, which is to be expected because of errors in beam measurement, variation in gas target density, etc.

A measurement of the efficiency of the detector system was performed by using 14-Mev *D–T* neutrons from the Los Alamos Cockcroft-Walton accelerator, from which the neutron flux is known approximately. The efficiency so measured was in agreement with that calculated from the known geometry of the detector and the *n–p* total scattering cross section value of Ageno *et al.*[7] The purpose of this measurement was to increase confidence that the behavior of the apparatus was well understood.

A minor correction was applied to account for multiple Rutherford scattering[8] of protons in the aluminum absorbers inserted between the third and fourth counters. An approximate calculation of the effect introduced a maximum correction of 1.3 percent. The method of calculation was checked experimentally, by use of the Cockcroft-Walton 14-Mev neutron source. For this check recoil protons were counted under conditions such that the Rutherford scattering was negligible; i.e., no scattering medium was present except the counter gas and the polyethylene radiator. Data were also taken with an aluminum absorber between the second and third counters under conditions such that the observed quadruple coincidence count was reduced by 18±4 percent. The approximate calculation applied to this case gave a reduction of 20 percent in agreement with the measurement.

III. RESULTS AND CONCLUSIONS

Table II gives a summary of results. The final corrected number of proton recoils is tabulated in column 7. The "near geometry" data are normalized to the "far geometry" data by the ratio of solid angles (0.1283) and are given in column 8. Tabulated errors represent the standard errors as calculated from the deviation of the different runs from the mean. In Fig. 2 these data, converted to the center-of-mass system (small effects of relativity are included), are plotted as a function of the angle of scattering of the neutron in the center-of-mass system. The vertical spread indicated on the plotted points is standard error. The horizontal spread indicated on the plot defines an angular range such that about 70 percent of the detected recoil protons appeared within this range. An experimental curve through the points has been drawn assuming symmetry around 90° as suggested by data at 40 and 90 Mev.[3,4] Only relative values of the differential cross section as a function of angle were measured in this experiment. However, with the assumption of symmetry about 90°, the data in Fig. 2 can be normalized so that integration over all angles gives the total cross section. A smooth curve through the experimental values of the total cross section as a function of energy gives a value[9] of 0.36 barn at 27 Mev. The differential cross section determined by means of this normalization is 32 mb per unit solid angle at 180° and 25 mb at 90°. For the ratio of the scattering at 180° to that at 90°, the present experiment yields a value of 1.28 with an over-all estimated error of ±8 percent. Of this error, 4 percent is the computed standard error, and the remaining 4 percent is a guess as to the systematic uncertainties arising from error in bias setting, Rutherford scattering, counting loss corrections, etc.

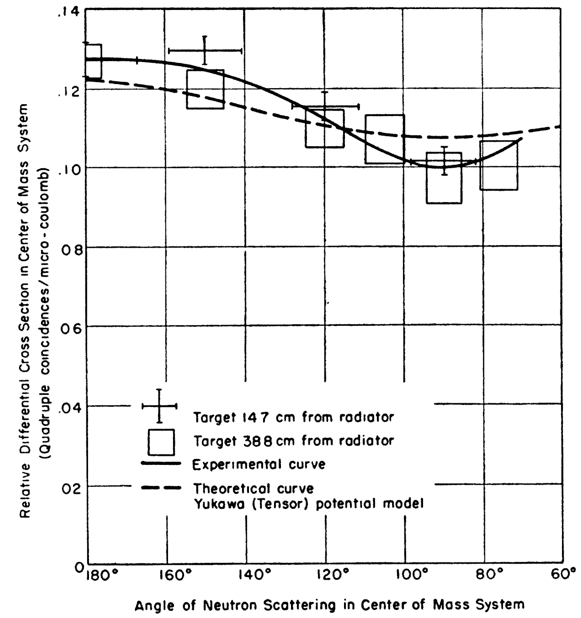

FIG. 2. Relative intensity of scattered neutrons *versus* angle of scattering of the neutron in the center-of-mass system. Standard errors are indicated by the vertical height of the symbols, while instrumental angular resolution is indicated by the width of the symbols.

The dashed curve shown in Fig. 2 is calculated in the manner of Christian and Hart[10] using a Yukawa potential with a range of 1.35×10^{-13} cm and with inclusion of a tensor force. Comparison of this theory to experimental data at 40 and 90 Mev is shown in Fig. 17 of reference 10. At 40 Mev this theory predicts the ratio at 180° to that at 90° to be 1.45, which is in fair agreement with, though less than, the experimental value of 1.55±0.2 measured by Hadley *et al.*[3] At 27.2 Mev the theory predicts a value of 1.15 which is also less than the experimental value of 1.28±0.10.

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