Angular Distribution of 14-Mev Neutrons Scattered by Tritons*

J. H. Coon, C. K. Bockelman, and H. H. Barschall
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

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Tritons recoiling from 14-Mev neutrons were observed in a coincidence counter telescope. The angular distribution of neutrons scattered through angles between 180° and 90° in the center-of-mass system was investigated. Absolute differential scattering cross sections were obtained by comparison with hydrogen. No evidence for the presence of disintegration protons or deuterons was found.

I. INTRODUCTION

In continuation of the survey of the interactions of tritons with light particles carried out at this laboratory[1] the angular distribution of 14-Mev neutrons scattered by tritons was investigated. The technique used in the present experiments is similar to that described previously in reports on the scattering of neutrons by protons[2] and by deuterons.[3]

II. PROCEDURE

Neutrons were obtained from the $T(d,n)He^4$ reaction as described previously.[2] Use was made of the neutrons emitted in a direction making an angle of 77° with the direction of the deuteron beam. The energy of the neutrons is calculated to be 14.3 Mev with a maximum energy spread of about ± 0.2 Mev. Their number was monitored by counting the alpha-particles from the same reaction.

Interaction of the neutrons with tritons was studied by observing triton recoils originating in a small gas cell and entering the counter telescope shown in Fig. 1. Argon mixed with about 3 percent CO_2 was used for the counter gas. Triple coincidences between the first three counters and quadruple coincidences between all four counters were observed.

The cross section for neutron-triton scattering was measured relative to the known cross section of hydrogen. For this comparison, the gas cell was filled alternately with 4.9 atmos of tritium gas and with the same pressure of normal hydrogen, and the number of recoiling tritons and protons was determined for the two fillings. Gas cell and counter telescope were joined by a 7/16-inch diameter aperture in which was mounted a 1-mil Dural window of stopping power equivalent to 5.0 cm of air.

In order to minimize the number of background coincidence counts produced by disintegration products originating in the wall of the cell, it was lined with clean 20-mil thick platinum sheet. The number of coincidence counts which were not produced by recoiling particles originating in the gas cell was determined by inserting the 20-mil thick platinum shutter shown in Fig. 1 between the gas cell and counter telescope. This shutter could be moved by means of a magnet placed outside the cell. A piece of 1-mil Dural foil, similar to that separating the gas cell and the counter, covered the platinum shutter to account for background particles originating in the Dural window.

The center of the gas cell was located at a distance of 11.3 cm from the neutron source. As a result of the finite sizes of the neutron source, of the gas cell, and of counter apertures, spreads $\Delta\theta$ (see Fig. 1) in the acceptance angle of recoiling particles were introduced as follows: for an angle setting of $\theta = 0°$, $\Delta\theta = \pm 9.5°$ for triple coincidences and $\pm 8.0°$ for quadruples; for an angle setting of $\theta = 45°$, $\Delta\theta = \pm 12°$ for triples and $\pm 10°$ for quadruples.

To facilitate handling the tritium sample, a small stainless steel tube containing uranium was attached to the gas cell. Whenever it was desirable to empty the cell, the uranium was allowed to absorb the tritium, which could be re-evolved by heating.

For the measurements with normal hydrogen the counters were filled to a pressure of 63 cm. The counter telescope was first set to detect protons recoiling in the forward direction. Since the energy loss of the recoils is smallest in the first counter, a bias curve was taken by observing coincidence counts as a function of the bias of the pulse-height discriminator which received

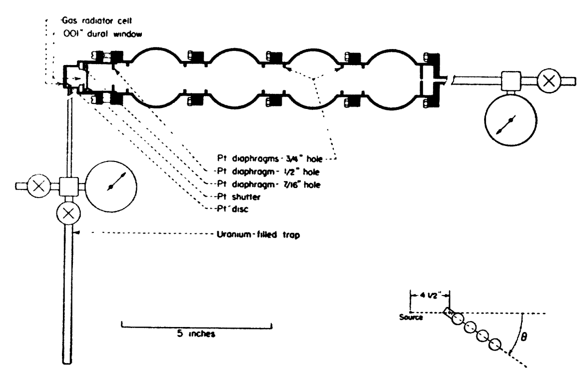

Fig. 1. Section through the axis of the counter telescope, consisting of four cylindrical counters. The telescope was rotated about the center of the gas radiator cell to measure particles recoiling at angles θ, as shown in the lower right-hand corner.

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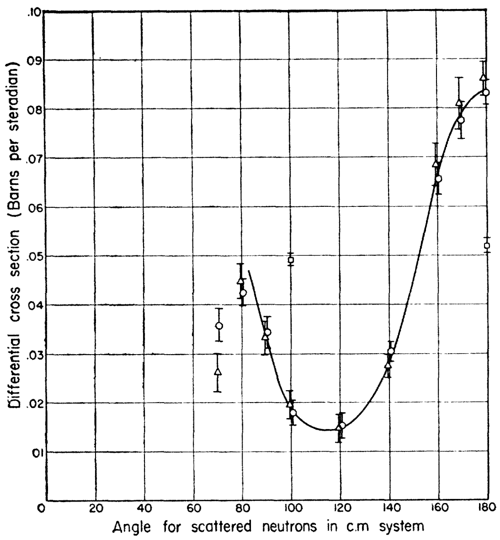

FIG. 2. Angular distribution data obtained by observing triple (circles) and quadruple (triangles) coincidence counts produced by recoil tritons. The squares are observations of recoil protons under similar conditions.

pulses from this counter. It was found that the coincidence counting rate was independent of bias over a wide range of biases. For the final determination of the number of recoil protons, biases on all four counters were set corresponding to the middle of the bias plateau of the first counter. Subsequently the number of proton recoils at 40° was determined, the bias settings for these data being the same as for the observations at 0°.

Since the tritium available for the present measurements contained about 35 percent hydrogen, and since it was desired to detect any products of the disintegration of tritium, it was necessary to establish the identity of the particles producing coincidence counts. For this purpose, the ranges and differences in specific ionization of the particles were used. Range determinations were carried out by varying the argon pressure in the counters.

With tritium in the gas cell, the axis of the counter telescope was set to detect particles at 0°, and the biases adjusted to detect all particles, including protons, deuterons (if any), and tritons. A predominant group of particles with a range of approximately 60 cm of air was found in good agreement with a range of 58 cm deduced for tritons recoiling at 0° from 14-Mev neutrons.

Disintegration particles may be produced by $(n,2n)$ and $(n,3n)$ processes. The $(n,2n)$ process may yield deuterons in the forward direction with energies up to 7.8 Mev (44-cm range), while the $(n,3n)$ process may yield protons with energies up to 4.8 Mev (32-cm range). Measurements of the range of particles at 0° indicated that within an accuracy of about 10 percent there were no particles with ranges between 55 cm and 9 cm, the lower limit of detection. Nine cm is the range of 2.3-Mev protons and 3.0-Mev deuterons. Therefore, these measurements do not indicate the presence of any disintegration particles, though they do not exclude disintegration processes producing mostly particles with ranges of less than 9 cm.

From the range measurement, the hydrogen impurity in the tritium sample could be determined, since with high pressure in the counters only the recoil protons had sufficient range to cause coincidence counts. A comparison with the number of counts observed when the gas cell contained normal hydrogen indicated a percent impurity of 35 ± 4.

With tritium in the gas cell, angular distribution measurements were made using 15-cm pressure in the counters. Since the foregoing measurements indicated that there were few, if any, detectable disintegration particles, adjustments were determined for measuring the angular distribution of the triton recoils over as great an angular range as possible. Tritons recoiling at 55° with respect to the incident neutrons in the laboratory system had barely enough range to reach the third counter and cause a triple coincidence count. When the angular resolutions given above are taken into account, it is found that at angle settings greater than 43° some of the recoiling tritons would be missed. Bias curves were taken at 0° and at 50° in the manner described for the case when the gas cell was filled with hydrogen. The energy loss of recoil tritons and recoil protons in the first counter for different angle settings is such that it is desirable to change the bias (in channel 1) with angle if one wants to be sure of detecting all the tritons but none of the protons. This bias change was made on the basis of the measured bias curves and the calculated change in energy loss with angle.

III. RESULTS

The results of the angular distribution measurements are shown in Fig. 2. Differential cross sections $\sigma(\phi)$ in barns/steradian are plotted in the center-of-mass system against the scattering angle ϕ of the neutron. Since, for the data taken with tritium in the gas cell, the biases were set so as to count all recoil tritons but no recoil protons, and since the results of the range measurements indicate that there is no measurable number of disintegration protons, the curve in Fig. 2 represents the angular distribution of $n-T$ scattering. Data obtained with hydrogen in the gas cell are also shown. For deducing the absolute value of the cross section, 0.050 barn/steradian was used for the differential cross section for scattering of neutrons by protons through 180° in the center-of-mass system.[2] Errors indicated in Fig. 2 are the standard errors arising from counting statistics. The average ratio of the observed triple coincidence count to the quadruple count was 1.98, in good agreement with the geometric solid angle ratio of 1.96.

The error in the scale of absolute values of $\sigma(\phi)$ is estimated to be ±20 percent. This estimate allows for a 10 percent uncertainty in the neutron-proton scattering cross section, 6 percent uncertainty in the purity of the tritium sample, and 5 percent statistical error. Errors introduced by Rutherford scattering are estimated to be negligible. The finite angular resolution will cause some broadening of the peak in the angular distribution at $\phi=180°$.

For the $n-T$ angular distribution measurements the background count observed with the platinum shutter in place averaged 30 percent for triple coincidences and 20 percent for quadruples. Accidental coincidences were calculated to contribute a background of less than one part in 10^4. For the data with hydrogen in the gas cell the corresponding backgrounds were about 20 percent and 10 percent. These backgrounds were lower because the higher counter gas pressure (63 cm instead of 15 cm) did not allow short range background particles to traverse all counters.

Integration of $\sigma(\phi)$ as plotted in Fig. 2 from 90° to 180° gives a value of 0.17 barn. If, as might be expected, the total cross section of tritium is greater than that of hydrogen (0.64 barn), there must either be a large peak in the angular distribution curve for scattering in the region from 0° to 90°, or a disintegration process which contributes a large fraction to the total cross section.

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Velocity Dependent Interactions and Nuclear Shells*

C. H. BLANCHARD† AND R. AVERY‡
University of Wisconsin, Madison, Wisconsin
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An investigation is made of the energy splitting of the two possible j values, $l\pm\frac{1}{2}$, of a single nucleon outside a closed shell resulting from the assumption of certain velocity dependent terms in the nucleon-nucleon interaction.

I. INTRODUCTION

THE modification[1] by Mayer of the nuclear shell model demands spin-orbit coupling such that the single nucleon state with $j=l+\frac{1}{2}$ is displaced in energy well below the state with $j=l-\frac{1}{2}$. It was suggested in a previous communication[2] that the splitting might be accounted for by terms in the nucleon-nucleon interaction which are linear in the nucleon momenta.

II. THEORY

We have considered the system of a single nucleon outside a nuclear core consisting of a closed shell of nucleons, and have investigated the splitting between the two possible j values which results from the velocity dependent interaction of the outside nucleon with the closed shell. The following notation is used for the quantum numbers involved:

k = orbital angular momentum of each of the $4(2k+1)$ nucleons in the closed shell (two neutrons and two protons in each of the $2k+1$ states).

l = orbital angular momentum of the outside nucleon.

$j=l\pm\frac{1}{2}$ = total angular momentum of the outside nucleon, and hence, of the entire system.

Let $U(k, l, j)$ be the average velocity dependent interaction energy of the outside nucleon with the closed shell. The difference

$$\Delta U(k, l)=U(k, l, l+\tfrac{1}{2})-U(k, l, l-\tfrac{1}{2})$$

gives the first-order splitting. Neither central nor tensor static forces can contribute to the splitting in first order.

It follows from the fact that the average velocity dependent interaction energy of an *entire* k shell with the l shell must vanish because of the transformation properties of the interactions, and from the ratio of the degeneracies of the $j=l+\frac{1}{2}$ and $j=l-\frac{1}{2}$ states, that

$$(l+1)U(k, l, l+\tfrac{1}{2})=-lU(k, l, l-\tfrac{1}{2}).$$

Thus

$$\Delta U(k, l)=[(2l+1)/l]U(k, l, l+\tfrac{1}{2})$$

and only the case $j=l+\frac{1}{2}$ need be evaluated.

The velocity dependent forces may be enumerated as

TABLE I. Energy splitting due to velocity dependent interactions.

n	$S_{\alpha\beta}^{(n)}T_{\alpha\beta}^{(n)}$	$\Delta U(k, l)$
1	$(\boldsymbol{\sigma}_\alpha+\boldsymbol{\sigma}_\beta)\frac{1}{2}(\tau_{\alpha3}+\tau_{\beta3})$	$Q(A-B)$
2	$(\boldsymbol{\sigma}_\alpha+\boldsymbol{\sigma}_\beta)\frac{1}{2}(1+\tau_{\alpha3}\tau_{\beta3})$	$A-B$
3	$(\boldsymbol{\sigma}_\alpha+\boldsymbol{\sigma}_\beta)\frac{1}{4}(3+\boldsymbol{\tau}_\alpha\cdot\boldsymbol{\tau}_\beta)$	$\frac{3}{2}(A-B)$
4	$(\boldsymbol{\sigma}_\alpha+\boldsymbol{\sigma}_\beta)\frac{1}{2}(1-\tau_{\alpha3}\tau_{\beta3})$	A
5	$(\boldsymbol{\sigma}_\alpha-\boldsymbol{\sigma}_\beta)\frac{1}{2}(\tau_{\alpha3}-\tau_{\beta3})$	QA
6	$[\boldsymbol{\sigma}_\alpha\times\boldsymbol{\sigma}_\beta]\frac{1}{2}[\boldsymbol{\tau}_\alpha\times\boldsymbol{\tau}_\beta]_3$	QB

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† Now at National Bureau of Standards, Washington, D. C.
‡ Now at Argonne National Laboratory, Chicago, Illinois.
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[2] Blanchard, Avery, and Sachs, Phys. Rev. 78, 292 (1950).