The Angular Distribution of Protons Scattered by High Energy Neutrons

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The scattering of 11-Mev neutrons by protons has been investigated. The neutrons from the disintegration of a beryllium target are collimated by a hole in a protective water wall. They are then scattered in a hydrogen gas cell and the recoil protons are observed at two different angles. The detection system consists of two parallel plate ionization chambers arranged so that protons may pass through both. Only coincidences are recorded thereby diminishing the very large neutron recoil background. The results indicate that the intensity of the protons varies as the cosine of the scattering angle in the laboratory system. Hence the scattering in the center of gravity system is isotropic within the experimental accuracy of ten percent.

INTODUCTION

KNOWLEDGE of the laws of force between the elementary nuclear particles is of fundamental importance. A direct way of studying these forces is to observe the scattering of elementary particles by each other. In this experiment an attempt has been made to study the angular dependence of the scattering of high energy neutrons by protons. The energy of the neutrons is made as high as practical in order to have their wave-lengths as short as possible. As the wave-length gets shorter the scattering should change from simple *s* scattering as the *p* scattering begins to show up. As a consequence the exchange properties of the forces begin to affect the scattering, as has been discussed in detail by Rarita and Schwinger.[1] The mean energy of the neutrons used in this experiment is 11 Mev.

EXPERIMENTAL METHOD

The basic experimental set-up is as follows: Neutrons from the cyclotron target are collimated into a beam by means of a hole in a water wall. This beam passes through a cell containing hydrogen gas, and the recoil protons are observed by suitable counters at various angles.

If a neutron of energy E_0 collides with a proton at rest, the energy of the proton E_p after being scattered through an angle θ is

$$E_p = E_0 \cos^2 \theta.$$

In this experiment beryllium is the cyclotron target, and the energy spectrum of the neutrons is continuous. For a given angle the proton energy distribution will also be continuous. In order to interpret the results under these conditions, a very detailed study of the particle spectrum would be necessary. Instead the energy of the protons observed is limited. The highest energy is set by the maximum energy of the emitted neutrons (13 Mev), and the lowest energy is set by the minimum range of the scattered protons after passing through aluminum foils. The mean energy of the neutron group for the forward direction is 11 Mev.

Since in the direct neutron beam the background owing to recoils is too high, it is necessary to make all measurements with the detector off the beam. The two angles chosen for measurement are 16° and 45°. Figure 1 shows the experi-

TABLE I. Energies of protons and neutrons.

Aluminum absorbers	16° Approx. thickness (inches)	16° mg/cm2	45° Approx. thickness (inches)	45° mg/cm2
Scattering cell window	0.006	43.3	0.002	12.7
Collimator window	0.001	6.8	0.001	6.8
Detecting chamber window	0.001	6.8	0.001	6.8
Detector internal foil	0.0007	4.3	0.0007	4.3
Additional absorber	0.006	43.3		
	0.002	12.7		
	0.0005	3.3		
Total		120.5		30.6
Equivalent air-cm ($1.52\ mg/cm^2 = 1$ air cm)		79.2		20.1
Correction for Al		4.7		0.3
Air distance (collimator to chamber)		2.7		2.7
Equivalent distance in first chamber (8.7 cm × pressure × stopping power of O_2)		16.7		10.1
0.3 cm-range in air to register in counter 2		0.3		0.3
Total range in air centimeters		103.6 cm		33.5 cm
Energy of protons detected (E_θ)		9.44 Mev		4.97 Mev
Energy of neutrons in forward direction (E_0)		10.2 Mev		10.1 Mev

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[1] W. Rarita and J. Schwinger, Phys. Rev. 59, 556 (1941).

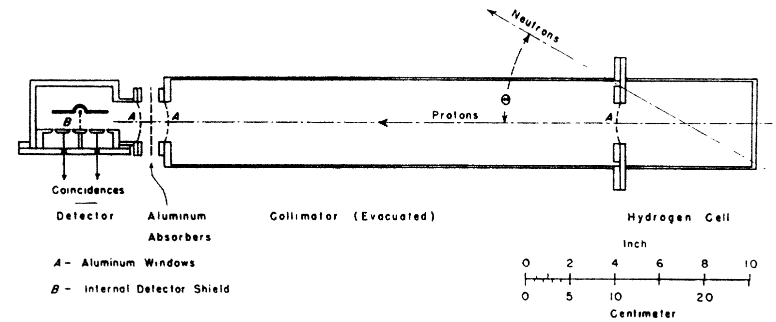

FIG. 1. Arrangement of detecting and scattering system.

mental layout of the scatterer and the detector system. The scatterer is the hydrogen gas in the scattering cell which is 14 cm deep. Its aperture is defined by the port 4.7 cm in diameter. Between this port and the detector is an evacuated collimating tube whose aperture is also 4.7 cm. Between the collimating chamber and the detector is an air gap of 2.7 cm. Here are placed the absorbing aluminum foils. There are aluminum windows on all the ports. Table I shows how the energy of the protons is determined.

THE DETECTING APPARATUS

The apparatus for detection of the recoil protons consists of two parallel plate type ionization chambers each connected to a separate pulse amplifier. The chambers are so arranged that a proton may pass through both. The simultaneous pulses from the amplifiers are recorded by means of a Rossi coincident circuit. Thus, to a large extent the background counting rate in each chamber owing to the recoils of the gas nuclei is eliminated.

In Fig. 2 is shown the plan of the double chamber. The separate chambers are 2.3 cm deep along the proton path, 2 cm wide, and 4 cm high. They are shielded from each other by a thin aluminum foil[2] perpendicular to the plane of their common collection plates.

In Fig. 3 is a block diagram showing the scheme by which coincidences are counted. In the mixing stage the output of the pulse amplifiers is fed to two separate gas triodes. The gas triodes have variable bias and act as discriminators. The output of the triodes go to pentodes arranged in a Rossi circuit. The advantage of this arrangement is that the pulses fed to the Rossi circuit are uniform since they are independent of the shape of the pulses at the input of the discriminators.

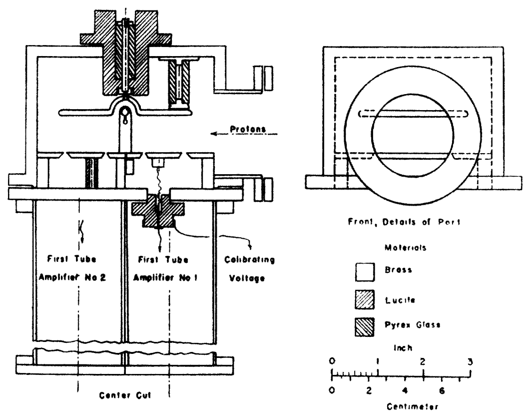

FIG. 2. Double coincident ionization chamber.

To see whether or not the apparatus would work as a true coincident circuit, use was made of the following relation:

$$n_c = 2tn_1n_2.$$

Here n_c is the chance coincident counting rate with independent counting rates in chambers 1 and 2 of n_1 and n_2, respectively, with resolving time t of the coincident circuit. Alpha-particle sources of various strengths were placed in chambers 1 and 2. It was found that the above relation was always satisfied independent of the individual counting rates and pulse size for $t = 1.2\times10^{-4}$ second.

Since a finely collimated beam of protons was

[2] When the apparatus was first tried out in the cyclotron room the shield foil was 1.5 air-centimeters. However, vibrations induced in the foil by the high noise level in the neighborhood of the cyclotron gave an intolerable voltage noise level to the apparatus. Dr. Geiger suggested that two foils be used instead of one. The two foils damped their individual vibrations so effectively that the foil was no longer a source of trouble.

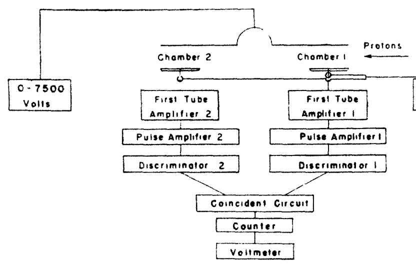

FIG. 3. Scheme for counting coincidences and calibrating the circuits.

not available, polonium alpha-particles are used to standardize the chambers. A thin source of polonium in a collimating tube is placed in the port of the double chamber so that the alpha-particles may pass through the center of both chambers. The pressure in the chamber is reduced until the "noise pulses" in the amplifier begin to mask the pulses from the alpha-particles. This is judged to occur at 7.2 cm of Hg pressure in oxygen. At this pressure the Po alpha-particles have a specific ionization of 95 kev per centimeter in chamber 1. The collecting voltage is 340 volts, which is equivalent to 3600 volts at atmospheric pressure. Since 7200 volts is the maximum available, it is possible to use the chamber up to 2 atmospheres of oxygen. At this pressure a beam of ionizing particles can be detected if it has a mean energy loss of at least 47 kev per air-centimeter. This is approximately the energy loss of 15-Mev protons at the beginning of their range.

The method used for counting the protons is such that the absolute sensitivity of the counters does not affect the final answer, only the relative sensitivity must remain constant. However, to assure reproducibility and uniformity, the manner of operation and efficiency of counting coincidences were investigated as follows. The sensitivity is determined first. The output of a thousand-cycle oscillator is rectified and sent through a milliammeter. The output of the oscillator also appears across a 20,000-ohm resistor. A small part of the output (that across one ohm) is fed onto a ring concentric with the leads from each ion chamber. By varying the oscillator output a series of pulses of any given size may be induced upon the first grids of the amplifiers. Their relative magnitude is read from the milliammeter. Although the induced pulses are all of the same size, they do not appear so at the output of an amplifier. This is because they are mixed with the random "noise pulses" on the first grid of an amplifier. In order to set the sensitivity of an amplifier at a specified value in spite of the distribution of output pulses, the pulses are counted at the output of a discriminator by a vacuum tube voltmeter. The discriminator gives pulses of equal size for each count. The oscillator output is varied until the voltmeter reads one-half what it would read when counting all the pulses (1000 per second). The reading of the oscillator milliammeter at this half value is called the "sensitivity" of the counter. This method of setting the sensitivity proved very useful during the course of making the measurements. It enabled us to check or set the sensitivity of each counter accurately and quickly.

The sensitivity of counter 2 is set, and the coincident counting rate is taken as a function of the sensitivity of counter 1. It was found that the counting rate would change less than 1 percent if counter 1 changed its sensitivity from 0.18 to 0.25, and counter 2 from 0.3 to 0.4 as both counters have a considerable "plateau" in their counting rate *vs.* sensitivity curve.

TEST FOR COLLIMATION

A test for the collimation was made in order to guard against spurious effects caused by scattering. Oxygen recoils in one chamber were counted as the chambers were moved across the beam. The sensitivity was set such that pulses of 2.7 Mev or greater tripped the counter. These recoils were from neutrons of 10 Mev or greater. The observed intensities were: 5 cm east of

TABLE II. Data on scattering. Columns 1 and 4 give the total number of counts observed for a particular day, while columns 2 and 5 give the respective number of millicoulombs of deuterons used. Columns 3 and 6 are, respectively, 1 divided by 2 and 6 by 7. Column 7 gives the hydrogen pressure in lb./sq. in. $P+b$ (protons plus background), b (background), mc (millicoulombs).

1 $P+b$	2 mc	3 $(P+b)$/mc	4 b	5 mc	6 b/mc	7 Press.	8 Θ
683	171	3.99 ±0.15	45	83	0.54 ±0.08	29.8	44°
409	122	3.6_6 ±0.17	43	57	0.7_6 ±0.11	29.8	44°
778	214	4.1_2 ±0.15	94	113	0.8_3 ±0.08	29.8	44°
659	203	3.2_5 −0.13	71	102	0.7_0 −0.08	28.5	44°
625	40	15.6 ±0.6	104	32	3.2 ±0.3	92	16°
808	59	13.8 ±0.5	137	41	3.3 ±0.3	94	16°
860	60	14.3 ±0.5	146	39	3.8 ±0.3	94	16°
282	63	4.5 ±0.3	230	66	3.5 ±0.2	0	16°
328	27	1.23 ±0.07	148	27	0.55 ±0.05	0	44°

center, 28.2±0.9; center, 27.4±0.9; 5 cm west of center, 28.1±0.9. Hence, the intensity was uniform over the region of the beam that was used.

CORRECTIONS FOR FINITE SOLID ANGLE

The most important correction that must be made in this experiment arises from the finite solid angle subtended by the detector at the scatter and by the neutron source at the detector. Variation of this solid angle with scattering angle is shown in Fig. 4. The distance between scatter and detector is taken as 62 cm. The diameter of the port is 4.7 cm, and the width of the detector slit is 2 cm. Furthermore, the projected width of the scatterer as seen from the target (4.2 meters away) is taken as 10.6 cm. The size of the correction depends also upon the variation of proton energy with angle and the energy spectrum.

Let $N(E)$ be the number of neutrons with energy greater than E in the forward direction. At 45° the energy for detection is set to have a minimum value E_d. It will be assumed that the variation of scattering cross section with energy is small. If θ is the angle of scattering, then the number of protons scattered between θ, $\theta+d\theta$ is

$$(\sigma_\theta/\sigma_0)N(E_d/\cos^2\theta)w(\theta)d\theta,$$

where σ_θ/σ_0 is the ratio scattering cross section at $\theta=0$ to $\theta=\theta$ and $w(\theta)$ is the relative solid angle (Fig. 4). The total number of particles observed is

$$N_\theta=\int_{\theta_{\min}}^{\theta_{\max}}\sigma_\theta/\sigma_0\, N(E_d/\cos^2{}_0)w(\theta)d\theta\Big/\int_{\theta_{\min}}^{\theta_{\max}}w(\theta)d\theta.$$

σ_θ/σ_0 is assumed to be independent of energy between $\theta_{\max}$ and $\theta_{\min}$ (41°–49°). $N(E)$ is found without serious error at 16°. The three values of $N(E)$ observed at 9.1 Mev, 10.2 Mev, and 11.3 Mev lie on a straight line within the accuracy of

TABLE III. Counts per millicoulombs of deuterons.

	A	B	C	D
16°	14.6 ±0.3	3.5 $\pm0.1_7$	4.5 ±0.3	3.5 ±0.2
45°	$3.7_2\pm0.07$	0.70±0.05	$1.2_3\pm0.07$	0.55±0.05

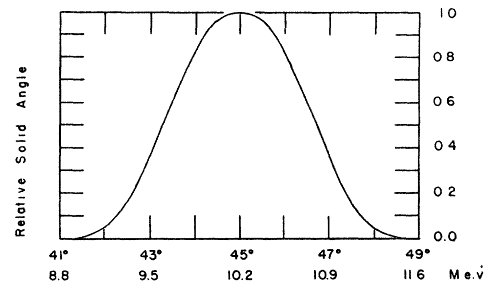

FIG. 4. Relative solid angle *vs.* the angle of scattering θ near 45° and the cut-off energies for θ.

the measurement (10 percent). Since $N(E)$ is a straight line function and $w(\theta)$ is symmetrical about the 45° position, the value of $N_{45°}$ observed is the correct one. Hence, a comparison of the number of particles observed at 45° and at 16° may be compared directly to find the ratio of cross sections.

PROCEDURE

First the angle is carefully laid out and the apparatus lined up. Then the proper thickness of aluminum foil is calculated so that the protons will have the correct cut-off energy (Table I). This must be done in conjunction with the oxygen pressure in the detecting chamber so that the energy loss of the most energetic protons will be sufficient for them to be counted. (The electrical sensitivity of the counters is always kept constant.) The field strength in the counters is also adjusted so that the ion collection time is constant. Then coincident counts A are taken at the proton cut-off energy for so many microcoulombs of deuterons. Then enough aluminum is interposed to cut out all protons due to neutrons of energy less than 13 Mev. This latter count B is due to a few proton recoils from neutrons of high energy, chance coincidences, and coincidences from all other causes. These runs are taken alternately—about twenty minutes apiece. After these data are obtained, similar sets of data are taken with no hydrogen in the scattering cell, C, D. The difference in count $(C-D)$ in this case is caused by n, p reactions in the scattering cell. The number of protons is given by $(A-B)-(C-D)$ for a given number of coulombs of deuterons on the beryllium target.

RESULTS

The results are best shown in Tables II and III. The net proton count at 16° is 10.1 ± 0.5 and at 45° is $2.3_4 \pm 0.1_3$ per millicoulomb of deuterons. The proton ratio is thus 4.3 ± 0.3. The ratio of gas pressures is $94/30 = 3.13$. Therefore, the ratio of scattered protons at 16° and 45° is $4.3/3.1 = 1.3_8 \pm 0.11$. If the scattering were isotropic in the center of gravity system, the proton intensity would vary as the cosine of the angle of scattering for constant solid angle. The ratio of the cosines of the scattering angles used is $0.96/0.70 = 1.37$. The numerical agreement is probably fortuitous as the statistical fluctuation of the measurements is one of the major difficulties in the experiment. For instance, a typical 14-hour run produces but 700 counts of protons with background, the background being 100 counts. Every precaution has been taken to make instrumental errors small. The amplifier sensitivity was checked at least every half-hour although the sensitivity would rarely change as much as 5 percent. The statistical error ($\sqrt{N}/N$) of a day's run was usually 7 percent. A series of runs separated by two weeks agreed within this fluctuation.

CONCLUSION

The experimental measurement of the scattering of 11-Mev neutrons on protons indicates that the scattering in the center of gravity system is isotropic. The accuracy is ten percent.

It is interesting to compare these results with those of Rarita and Schwinger.[1] They made calculations on high energy n,p scattering for three types of forces between these particles. At the energies used in this experiment, the predicted asymmetry for the forces similar to those predicted by "symmetrical" and "charged" meson theories is very small and well within the experimental error. The third type of force analogous to the "neutral" meson theory predicts about 60 percent more recoils in the forward direction at 11 Mev. Experimentally such asymmetry does not seem to exist. Hence, it would appear that exchange forces similar to the first two agree better with the experiment.

A word about the possibilities of extending the range of the measurement might be of interest at this point. For carrying out this particular experiment, the scattered intensity could be increased considerably by getting closer to the cyclotron and imposing thicker water walls for better collimation. The ion chambers could perhaps be improved so as to increase their effective resolving power. Under such circumstances, it might be possible to extend the measurements into the region of 20 million volts. As a test, a thick (to the proton) paraffin scatterer instead of hydrogen gas was placed before the detector. With lithium as a target it was found the proton owing to neutrons of from 20 to 24 Mev could be detected by the apparatus. A feasible experiment with the present set-up would be to measure the total scattering cross section of hydrogen in the energy region between 5 and 20 Mev.

It was originally intended that this program of research on the properties of high energy neutrons would be carried through as outlined above, and that the present results would be considerably extended in accuracy and reliability. However, because of present conditions, the work must be terminated at this point, and the report is presented not as a final report but as indication of present progress.

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