THE RICE INSTITUTE

THE ANGULAR DISTRIBUTION OF NEUTRON-PROTON

SCATTERING AT 21.6 MEV. AND AT 15.2 MEV.

by

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A THESIS
SUBMITTED TO THE FACULTY
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF ARTS

Houston, Texas
May, 1956
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I. INTRODUCTION

The experimental study of the scattering of neutrons by protons is of interest because such studies furnish useful information about the nature of nuclear forces, and in particular, about the forces between nucleons, the fundamental problem in nuclear physics.

Many measurements have been made of the angular dependence of the n-p differential cross section for scattering in the center of mass system for various neutron energies. For a neutron energy of 14.1 Mev., the three\(^1\)\(^3\) most recent experiments indicate a small anisotropy about 90 degrees in the center of the mass system. The best value of \(\frac{\sigma_{90}}{\sigma_{0}}\) has been computed to be 1.05±.02. At 17.9 Mev., \(\frac{\sigma_{90}}{\sigma_{0}}\) equals 1.03±.03.\(^4\)

At 27.2 Mev., \(\frac{\sigma_{90}}{\sigma_{0}}\) equals 1.28±.10.\(^5\) At still higher energies, progressively greater anisotropy has been found. It was the purpose of this experiment to make a measurement of the anisotropy at some energy near 20 Mev.

The source of neutrons was provided by the T(d,n)He\(^4\) reaction which has a Q of 17.6 Mev. Both of the Rice Institute's Van de Graaff accelerators were used in this experiment. The smaller of the two, which can reach 2.0 Mev., can furnish neutrons of energies between 12 Mev. and 18 Mev., depending on the bombarding energy of the deuteron and the laboratory angle chosen. The larger machine, which can reach better than
5 Mev., can in the same manner furnish us with neutrons of energy between 12 Mev. and better than 22 Mev. The data from the 5.0 Mev. machine was taken at a deuteron bombarding energy of 4.69 Mev. which gives a neutron energy of 21.6 Mev. in the forward direction. The 2.0 Mev. Van de Graaff was used to accelerate deuterons to 200 Kev. which produces 15.2 Mev. neutrons in the forward direction. The data at 15.2 Mev. was taken essentially as a check on the procedure.

The angular distribution of the neutron-proton scattering was found by observing the recoil protons originating in a thin hydrogenous foil placed in the neutron beam at various angles to the beam. A scintillation counting method was used to detect the recoil protons for proton angles of from 0 degrees to 75 degrees in the center of mass system, and a gas proportional counter in coincidence was used to insure that only recoil protons were counted in the scintillation counter.
II. A. EXPERIMENTAL APPARATUS (21.6 Mev.)

The tritium target used in this experiment as a source of high energy neutrons consisted of tritium gas absorbed in a layer of Zr metal which had been evaporated onto a tungsten backing. The target used was approximately 40 Kev. thick at a proton energy of 1 Mev. Therefore there is no appreciable energy loss by the deuteron in the target at the higher bombarding energy.

The neutron spectrometer described by Arthur Cole in his master's thesis, 1953, was used as a detector. See Fig. 1. The spectrometer consists of a gas proportional counter enclosed in an aluminum shell, plus a scintillation counter, whose NaI crystal is contained in the back face of the aluminum can. The sodium iodide crystal is joined optically to a photomultiplier tube which extends from the back of the aluminum shell. Inside the aluminum can, mounted concentrically to its inner walls, is a 1 mm. thick brass cylinder which defines the volume of the gas proportional counter itself. There are 3 cm. holes drilled in this brass cylinder on its front and back faces. These holes are centered along the axis of symmetry of the radiator and crystal. Between the inner wall of the aluminum shell and the outer wall of the brass cylinder is a carriage which makes it possible for one to place various thicknesses of polyethylene in the neutron beam.
NEUTRON SPECTROMETER

FIG. 1
In this experiment only two of the four possible carriage positions were used: the thickest radiator position and the blank position. The thickest radiator position placed a foil of polyethylene 1 in. in diameter and 38.5 mg/cm.\(^2\) thick in the neutron beam. The blank position, as the name implies, placed nothing in the path of the neutrons.

The gas counter and the NaI counter together form a coincidence circuit for the detection of the recoil protons which originate in the polyethylene. Low energy electrons can cause a pulse of the same order of magnitude as a high energy proton in the gas counter, but these can cause only accidentals, since they are, for the most part, eliminated by the bias on the pulse height analyzer. A bias on the gas-counter discriminator serves to eliminate pulses due to high energy electrons from gamma radiation which might cause a pulse in the NaI crystal of the same size as the recoil proton pulses. The gas-counter was filled to one atmosphere of argon plus 5% CO\(_2\).

A block diagram of the electronics involved is shown in Fig. 2. The discriminators of both amplifiers were set at 10.0 volts to insure that the coincidence pulses were caused by recoil protons. Since the rise time of a pulse in the gas counter is longer than the rise time of a pulse in the scintillation counter, the NaI discriminator triggers earlier and a \(3/8\) microsecond delay line was introduced between the NaI counter discriminator and the coincidence circuit to insure that
BLOCK DIAGRAM OF ASSOCIATED ELECTRONICS

FIG. 2

TO MULTICHANNEL ANALYSER

1 µSEC DELAY
the two discriminator pulses reached the coincidence circuit at the same time. When two pulses in coincidence reached the coincidence circuit, a pulse was generated which opened the gate on the 20-channel analyzer, permitting the pulse from the NaI amplifier output, delayed for 3 microseconds, to register in the 20-channels.

The 20-channel base line was set to accept the lowest energy proton expected from the radiator (the proton having traversed the entire radiator thickness) at the angle under investigation. While in principle it is perhaps unnecessary to measure the pulse height spectrum for each point, since data is taken with and without radiator, nevertheless the pulse spectrum was an important practical check on the trustworthiness of the data and was taken at each point.
II. B. EXPERIMENTAL PROCEDURE (21.6 Mev.)

The vertical diameter of the radiator was the axis of rotation, and this axis was fixed visually by suspending a pointer above the rotating table to which the spectrometer was fixed and rotating the spectrometer to see if a shift from the axis of rotation could be observed. A further check on alignment was obtained by taking data at the same angles on both sides of the forward direction of the beam. If the true zero angle is seriously in error, the maximum for the observed recoil energy distribution will differ for a given angular setting on the two sides of the beam. Taking data on both sides also has the advantage that errors in the anisotropy due to small errors in alignment would cancel on averaging.

The NaI crystal used was 70 mils thick and 3/4 of an inch in diameter. This thickness was calculated to be enough to stop a 19 Mev. proton. The distance from the tritium target to the radiator was 7.5 cms. From the radiator to the crystal, the distance was 10.0 cms, as fixed by the construction of the spectrometer.

The base line of the 20-channel analyzer was set at 20.0 volts and was not changed during the course of the experiment. Since each channel of the 20-channel analyzer is 0.5 volts wide, the distribution of pulses can be observed from
20 to 30 volts and all pulses above 30 volts will register in the surplus count of the analyzer. The gain of the linear amplifier was always set to make all the recoil proton pulses from the radiator rise above the 20 volt bias.

We know \( E_p = E_n \cos^2 \theta \), where \( \theta \) is the lab angle between the forward direction of the beam and the horizontal axis of the counter. As the angle \( \theta \) is increased, the energy of the recoil protons decreases and so does the pulse height from the NaI crystal. Therefore the gain of the NaI linear amplifier must be increased. This will also increase the singles counting rate of the scintillation counter, since background due to high energy electrons and to protons from \((n,p)\) reactions in the metal walls of the counter is always present in larger numbers at the lower energies. The accidental rate = \( 2T n_1 n_2 \) where \( T \) is the resolving time of the coincidence circuit and is equal to 1 microsecond, where \( n_1 \) is the singles counting rate in the proportional counter, and where \( n_2 \) is the singles counting rate in the scintillation counter. Therefore reducing the gain of the proportional counter will help to compensate in part for the increase in the rate of accidental coincidences. This is possible because the specific ionization in the gas increases with decreasing proton energy. Therefore the gain of the gas counter was decreased in such a manner that the height of the pulse produced by the recoil proton was approximately
the same for each angle. This was done so that the timing in the coincidence circuit would be unchanged. This procedure kept the background at angles less than $45^\circ$ to a reasonable percentage of the total count. At angles greater than $45^\circ$, however, the accidental rate was very high, and the background was a very large percentage of the total count. This fact limited our investigation to laboratory angles of less than $45^\circ$ for the recoil protons.

Using the $0^\circ$ peak as a starting point, the appropriate gains for each angle were computed for the two amplifiers and these gains were used throughout the experiment. These gains were computed with the assumption that the proton would lose a negligible amount of energy in the radiator and gas except at the larger angles, and that the crystal was thick enough to completely stop the highest energy recoil protons.

Counts were taken for proton recoil angles of $0^\circ$, $10^\circ$, $20^\circ$, $30^\circ$, $37.5^\circ$, and $45^\circ$ on both sides of the beam, first with the radiator in place and then without it. Each count was taken for the same number of integrator counts, that is, for the same number of deuterons striking the tritium target. Each count took approximately the same amount of time. The data showed no trend which would indicate the evaporation or exhaustion of a large amount of tritium from the target.

The recoil proton energy distributions are shown in
Figures 3-8. These figures represent the combined data. For example, Fig. 5 shows the number of counts per channel at +20° and -20°. The data has been normalized by dividing the baseline voltage and the voltage spread by the NaI amplifier gain. Therefore these histograms have voltages which are directly proportional to the energies lost by recoil protons in the crystal. We have a check on the data from the ratios of peak voltages at various angles, since the ratio of the energies of the recoil protons can be computed exactly from the relation

\[ E_p = E_n \cos^2 \theta \]

minus the energy loss in the radiator and gas. These calculations are in agreement with the observed data at those angles where a peak in the voltage distribution is visible from the histograms Figs. 3-8 and in agreement with the calculation that the NaI crystal is at least thick enough to completely stop a 19 Mev. proton. At angles greater than 30°, it is impossible to see where the peak in the angular distributions lies. There are several reasons for this.

First, energy resolution becomes progressively poorer at larger angles. If ideal geometry were possible we would have essentially a point radiator with a collimated beam of neutrons incident on it and the energy resolution

\[ \frac{\Delta E}{E} = \frac{\cos^2 \phi - \cos^2(\theta + \phi)}{\cos^2 \phi} \approx 2 \phi \tan \phi \]
where $\theta$ is the laboratory recoil proton angle and where

$$\phi = \arctan \frac{\frac{1}{2} \times \frac{3}{4} \times 2.54}{10.0} = 5.46^\circ$$

which is the angle between the lines joining the center of the crystal and the outer edge of the crystal to the center of the radiator. Second, for lower energy recoil protons, there is a greater energy loss in the radiator and gas, thus increasing further the energy spread at larger angles. Third, at larger angles, neutrons striking the edges of the radiator will cause a further spread in energy. For these reasons statistics in each channel are not good enough to show a peak at angles greater than $30^\circ$. At $37.5^\circ$, calculations show that the peak should lie in the high voltage end of the 20-channels. The data at $45^\circ$, however, shows neither a peak nor a "hole," and the calculations done indicate that the peak should lie very close to the low voltage end of the 20-channels. For this reason the data at $45^\circ$ has been discarded before making the final calculations.

Backgrounds varied from 25% under $0^\circ$ peak to 63% under the $37.5^\circ$ peak.
FIG. 4

10°

COINCIDENCE COUNTS

PULSE HEIGHT (VOLTS)

75

50

25

10

15
FIG. 6

30°

COINCIDENCE COUNTS

PULSE HEIGHT (VOLTS)

7.62

11.42
FIG. 7

37.5°

276

IN
SURPLUS

6.40  PULSE HEIGHT (VOLTS)  9.60

COINCIDENCE COUNTS

75-

50-

25-
III. A. EXPERIMENTAL APPARATUS (15.2 Mev.)

The same counter or spectrometer that was used for the investigation of the 21.6 Mev. n-p angular distribution was used for the investigation of the n-p angular distribution at 15.2 Mev. The detection equipment is the same as in Fig. 1 except that the 20-channel analyzer has been replaced by a photographic method of recording. A different gate circuit replaces the gate of the 20-channel analyzer. The NaI pulses must pass through this gate, which opens only when a pulse from the coincidence circuit opens it. The output of the gate passes to a Tektronix model 514 D oscilloscope. A Du Mont oscilloscope camera was mounted on the oscilloscope to take pictures of the pulses produced in the scintillation counter. This method provides us, in effect, with a multi-channel analyzer, since the distribution of pulses on the film can be read so as to divide the voltage range covered into many smaller differential increments. It also has the advantage over the 20-channel analyzer that it can differentiate over an effective voltage range of 50 volts, while the 20-channel device can do so only for a 10 volt range. The principal disadvantage of this method is the length of time taken to read the pulse height distribution from the film.

The Rice Institute's 2.0 Mev. Van de Graaff accelerator was used to accelerate deuterons to 200 Kev. Two-thirds of
the accelerating tube was shorted out, and the pressure in
the tank was varied until a maximum in the number of neutrons
produced was found. This maximum corresponds to the resonance
for the T (d,n)He\(^4\) reaction at 200 Kev. The detector used here
was a long counter.

During the experiment, the pressure was kept at this
experimentally found value, and the long counter was used as
a monitor. The monitor was kept in a fixed position, and
each angular measurement was taken to the same number of
monitor counts. The data is thus normalized to the same
number of neutrons produced in the target and not to the
same number of deuterons incident on the target.

The geometry used was the same as that used previously
at 21.6 Mev.
Counts and backgrounds were taken at $0^\circ$, $10^\circ$, $20^\circ$, $32.5^\circ$, and $37.5^\circ$, all on the same side of the beam. The gains used were computed as before, but an attempt was made to compensate for the fact that lower energy recoil protons lose more energy in the radiator and gas. As a result the NaI amplifier gains for larger angles were slightly overestimated (See Figs. 9-13). For the larger angles the upper end of the pulse height distribution cannot be seen since anything greater than a 50 volt pulse will register as a 50 volt pulse.

Figs. 9-13 have been normalized by dividing the initial voltage spread of 50 volts by the ratio of the NaI amplifier gain at an angle $\theta$ to the gain at $0^\circ$. These figures represent the counts per "channel" with background subtracted.
IV. RESULTS

The yields are plotted in Fig. 14 against the center of mass scattering angle of the neutron. Least squares fits to the data were made for the function $1 + k \cos^2 \theta$.

A measure of the closeness of fit is

$$s^2 = \frac{1}{n-2} \sum_{i=1}^{n} \left[ \frac{\sigma_{\text{calc}}(\theta_i) - \sigma_{\text{exp}}(\theta_i)}{\varepsilon_i} \right]^2$$

where $\varepsilon_i$ is the error assigned to the $i$th point and where $n$ is the number of experimental points: 5 in the cases of both 15.2 Mev. neutrons and 21.6 Mev. neutrons. A good fit has $s^2 \approx 1$.

For 21.6 Mev. neutrons the value of $k$ was found to be 0.19, with $s^2 = 0.80$. The maximum statistical error involved was about 8%.

For 15.2 Mev. neutrons the value of $k$ was found to be 0.038, with $s^2 = 1.73$. The maximum statistical error involved here was about 6%.

The data in the lower curve of Fig. 14 has been normalized to the total n-p cross section of 415 millibarns at 21.6 Mev. The data in the upper curve has been normalized to the total n-p cross section of 630 millibarns for 15.2 Mev. neutrons.
At 21.6 Mev. the value of $k$ found—0.19—is reasonable since we expect a value somewhere between 0.08 and 0.28 as found for neutron energies of 17.9 Mev. and 27.2 Mev. respectively.

The data at 15.2 Mev., which was obtained essentially as a check on procedure is reasonable since previous experimental work indicates that the value of $k$ should lie between 0.05 and 0.08. The poor fit of the curve in Fig. 14 is probably explained by the fact that the incident neutrons were not monoenergetic but possessed a considerable spread in energies and also by the fact that deuteron bombarding energy could have shifted slightly without being noticed, thus changing the neutron bombarding energy. Nevertheless, that data taken at 15.2 Mev. gives support to the premise that the procedure at 21.6 Mev. was correct.
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ACKNOWLEDGEMENTS

The author wishes to express his thanks to Dr. Risser for suggesting this project, and aiding in its completion. Thanks are due to Dr. Shalek at M.D. Anderson hospital for the loan of the oscilloscope camera. Thanks are also due to J. Price and the men of the Physics shop.