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Chih, Chung Ying.

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A CLOUD-CHAMBER STUDY OF THE SCATTERING CROSS SECTION
OF PROTONS BY 90-MEV NEUTRONS AT EXTREME ANGLES

Chung Ying Chih
(Thesis)

May, 1954

Berkeley, California
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Chung Ying Chih
Radiation Laboratory, Department of Physics
University of California, Berkeley, California

Contents

Abstract ............................................................................. 3
I. Introduction...................................................................... 4
II. Results and Conclusions.................................................. 7
III. Experimental Procedures
   (3.1) Neutron Beam.......................................................... 16
   (3.2) Collimation System................................................... 17
   (3.3) The Cloud Chamber................................................ 19
   (3.4) Operation............................................................... 19
   (3.5) Photography............................................................ 21
IV. Measurements and Reduction of Data
   (4.1) Reprojection Apparatus............................................ 23
   (4.2) Details of Measurement............................................ 23
   (4.3) Acceptance Criteria............................................... 25
   (4.4) Details of Calculation.............................................. 26
   (4.5) Range-Energy Relation........................................... 30
V. Discussion of Errors
   (5.1) Errors in Energy Determination............................... 33
   (5.2) Errors in Cross-Section Determination..................... 35
Appendix. ............................................................................ 38
References.......................................................................... 42
A CLOUD-CHAMBER STUDY OF THE SCATTERING CROSS SECTION OF PROTONS BY 90-MEV NEUTRONS AT EXTREME ANGLES

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ABSTRACT

An investigation of 90-Mev neutrons scattered by protons has been conducted with a cloud chamber filled with hydrogen or with a mixture of methane and hydrogen in a magnetic field of 22,000 gauss. The neutron energy spectrum has a full width at half maximum of about 30 Mev. The neutron scattering angles range from $8^\circ$ to $180^\circ$ in the center-of-mass system. The differential scattering cross section is found to have a symmetry about $90^\circ$ in the center-of-mass system. Detailed results, with a likely theoretical inference, a discussion of errors, and a description of experimental apparatus and procedure, are also presented.
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I. INTRODUCTION

At the present time, there is no satisfactory fundamental theory of nuclear forces. Increasing effort is being devoted to experiments that may lead to an understanding of these forces. There are several approaches to this end. One of the most fruitful has been the experimental study of those problems in which only two nucleons are involved, that is, the nuclear two-body problems. Of great importance among these are the neutron-proton scattering experiments.

In the early thirties, a number of n-p scattering experiments were performed to determine the angular distribution of the scattered neutrons, with highly contradictory results.\(^1\) Later experiments\(^2\)\(^-\)\(^8\) with neutron energies up to 15 Mev show a spherical symmetry or near-symmetry of this distribution about the center of mass of the moving system. While in some experiments\(^6\),\(^8\) the scattering is still isotropic at about 14 Mev, some other experiments\(^4\),\(^5\) in the neutron energy range of 9 to 14 Mev show a slight asymmetry, favoring the scattering of neutrons in the backward direction in the center-of-mass system. It is now generally accepted that the scattering is spherically symmetric with neutron energies up to about 10 Mev. None of these low-energy and medium-energy experiments gives information concerning the explicit radial dependence of the forces or of those forces in other than S states, and in fact even the ranges of the forces are determined only approximately.\(^9\)
The latter statement can be visualized in the following elementary way. Quantum-mechanically, the spherical symmetry of the scattering corresponds to an $S$ wave, that is, a wave of zero orbital angular momentum. For the scattering to be attributable to neutrons in the $S$ states only, the neutron in the $P$ state should be outside the range of nuclear forces. Let $b$ be the closest distance between the proton and the undeflected neutron of orbital angular momentum $\hbar$, and let $R$ be the range of the neutron-proton force. Then

$$b > R$$

is the condition for the neutron just to be outside the range of the nuclear force. The orbital angular momentum of this $P$-state neutron is

$$|\vec{L}| = \pi = \mu b v = \left(\frac{1}{2} M \right) b \left(\frac{2E}{M}\right)^{1/2} = b \left(\frac{EM}{2}\right)^{1/2},$$

where $\mu$ is the reduced mass of the neutron-proton system, $v$ is the initial relative velocity between neutron and proton, $M$ is the approximate neutron or proton mass, and $E$ is the initial neutron energy in the laboratory system. We have then

$$R < b = \pi \left(\frac{2}{EM}\right)^{1/2} \approx 2.8 \times 10^{-13} \text{ cm}$$

for $E = 10$ Mev.

To secure more information about these nucleon-nucleon forces, it is very desirable to perform experiments at high energies so that neutrons of nonzero orbital angular momentum may pass close enough to the proton to be within the range of the nuclear forces. The angular dependence of the differential $n-p$ scattering cross section at high energy yields information primarily concerning the exchange character of the forces. Of particular interest is the scattering at 90 Mev, where the theoretical dilemma arises. A more detailed discussion in this respect is given under "Results and Conclusions".
Neutron-proton scattering experiments at 90 Mev were performed in the past few years by a number of observers with a cloud chamber, with proportional counters, with scintillation counters, and also with nuclear emulsions. These experiments, however, did not extend the neutron scatter angles far enough into the small-angle region to prove or disprove conclusively the rising trend of the differential scattering cross section in that region. At the time this experiment began in 1951, the smallest neutron angle ever investigated was 12° in the center-of-mass system. This had been done by Powell and co-workers. The present experiment extended the neutron angles to 8° in the center-of-mass system. The accuracy was greatly enhanced in this experiment by measuring a greater number of tracks and by using improved equipment.
The experiment here reported extended over a period of three years. Three runs were made. A total of 5019 actual tracks was carefully measured. The following table shows the operating conditions for the three runs.

Table I
Operating Conditions for the Three Runs

<table>
<thead>
<tr>
<th></th>
<th>Chamber Gas</th>
<th>Chamber pressure</th>
<th>Chamber temperature</th>
<th>Cycle of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Run (1951)</td>
<td>98.1% hydrogen 1.9% water vapor</td>
<td>89.7 cm Hg</td>
<td>19.5°C</td>
<td>~1 min.</td>
</tr>
<tr>
<td>Second Run (1952)</td>
<td>56.5% methane 41.5% hydrogen 2.0% water vapor</td>
<td>84.1 cm Hg</td>
<td>19.5°C</td>
<td>~1 min.</td>
</tr>
<tr>
<td>Third Run (1953)</td>
<td>98.0% hydrogen 2.0% water vapor</td>
<td>89.3 cm Hg</td>
<td>19.3°C</td>
<td>~2 min.</td>
</tr>
</tbody>
</table>
The analysis of the first run (1951) was devoted to neutron angles lying between $8^\circ$ and $40^\circ$, and between $140^\circ$ and $180^\circ$, in the center-of-mass system. This was done because they are the most crucial regions in determining whether or not there is a symmetry of the differential scattering cross-section curve about $90^\circ$ in the center-of-mass system. Furthermore, as the earlier experiments had not extended the neutron angles far enough into the small-angle region, it was desirable to put special emphasis on it.

A total of 1738 actual tracks was measured from pictures of the first run. The angular distribution of the differential $n-p$ scattering cross section obtained in this run is shown in Table II and Fig. 1.

Table II
Differential Cross Sections from the First Run

<table>
<thead>
<tr>
<th>Neutron Angles</th>
<th>Number of Tracks</th>
<th>Weighted Number of Tracks</th>
<th>$\sigma$ (mb per steradian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$8^\circ - 10^\circ$</td>
<td>18</td>
<td>40.4</td>
<td>$13.5 \pm 3.2$</td>
</tr>
<tr>
<td>$10^\circ - 20^\circ$</td>
<td>177</td>
<td>260</td>
<td>$10.4 \pm 1.0$</td>
</tr>
<tr>
<td>$20^\circ - 30^\circ$</td>
<td>195</td>
<td>425</td>
<td>$10.4 \pm 0.7$</td>
</tr>
<tr>
<td>$30^\circ - 40^\circ$</td>
<td>213</td>
<td>451</td>
<td>$8.1 \pm 0.6$</td>
</tr>
<tr>
<td>$140^\circ - 150^\circ$</td>
<td>390</td>
<td>390</td>
<td>$7.0 \pm 0.4$</td>
</tr>
<tr>
<td>$150^\circ - 160^\circ$</td>
<td>396</td>
<td>396</td>
<td>$9.7 \pm 0.5$</td>
</tr>
<tr>
<td>$160^\circ - 170^\circ$</td>
<td>311</td>
<td>311</td>
<td>$12.4 \pm 0.7$</td>
</tr>
<tr>
<td>$170^\circ - 180^\circ$</td>
<td>98</td>
<td>98</td>
<td>$11.6 \pm 0.7$</td>
</tr>
</tbody>
</table>

(Energy $\geq 40$ Mev, $0^\circ \leq \alpha \leq 40^\circ$)
Fig. 1. Differential Cross Sections from the First Run
The data of the first run in the $140^\circ - 180^\circ$ region were normalized to those of the third run in the same region. This same normalizing factor was used for the small-angle region.

The neutron energy spectra, obtained from forward proton tracks (neutron angles from $140^\circ$ to $180^\circ$ in c.m. system) and from sidewise proton tracks (neutron angles from $8^\circ$ to $40^\circ$ in c.m. system) are separately shown in Fig. 2. The theoretical curve predicted by Serber is also shown in the figure. It is noted that aside from the difference in positions of the peaks, the two experimental neutron energy spectra agree remarkably with the theoretical curve. The full width at half maximum is about 30 Mev in both experimental curves, as was predicted by the theory. A simple derivation is given in Section (3.1) entitled "Neutron Beam". Because the energy determination was comparatively difficult for wide-angle proton tracks, the neutron-energy spectrum from wide-angle proton tracks is broader than that obtained from the forward group. The excellent agreement of the two experimental energy spectra with each other and with the theoretical curve is regarded as most satisfactory. This agreement in the neutron energy spectra insures that no significant number of tracks was overlooked or incorrectly measured.

An inspection of Fig. 1 and Table II readily convinces one that for these regions there is a symmetry of the differential scattering cross section about $90^\circ$ in the center-of-mass system. This conclusion is further supported by the fact that there were practically equal numbers of weighted proton recoils in the forward direction and in the wide-angle direction: 1195 and 1176 respectively. However, because of the theoretical difficulty resulting from this symmetry (discussed later in this section), it was felt that further investigations should be made before any conclusion was drawn.

Therefore, investigations of two more runs were made: 1122 actual tracks (as distinguished from weighted tracks) were measured from pictures of the second (1952) run, which were separately investigated by Kellogg for carbon stars; and 2159 actual tracks were measured from pictures of the third (1953) run. The measurements of both the second and third runs covered all neutron scatter angles, except those in which the tracks of the scattered protons were too short to be observed and
Fig. 2. Neutron Energy Spectra
measured. This lower limit of the neutron angles, which is determined by the stopping power of the gas in the chamber, was 10° 20′ for the second run and 8° for the third run. In other words, the second run covered neutron angles from 10° 20′ to 180° and the third run from 8° to 180° in the center-of-mass system. The data of both the second and the third runs were separately normalized to the total cross section of 76.0 millibarns. 16, 21

Out of the third run two energy groups were studied separately. The first group consisted of neutrons of energies from 40 Mev to 70 Mev, and the second group consisted of neutrons of energies from 90 Mev to 130 Mev. While the differential cross section showed symmetry about 90° in the center-of-mass system for the first group, a slight asymmetry was noted for the second group, favoring the scattering of neutrons in the backward direction in the center-of-mass system. Only in this run was any such asymmetry noted.

In obtaining the combined results of the differential scattering cross section for the three runs, the average was taken, weighted proportionally to the actual number of tracks measured. Table III and Fig. 3 show the combined results of the three runs.
Table III
Combined Results of the Three Runs

<table>
<thead>
<tr>
<th>Neutron angle in c.m. system</th>
<th>Millibarns per steradian</th>
</tr>
</thead>
<tbody>
<tr>
<td>$8^\circ$ - $10^\circ$</td>
<td>$12.5 \pm 2.6$</td>
</tr>
<tr>
<td>$10^\circ$ - $20^\circ$</td>
<td>$9.6 \pm 0.7$</td>
</tr>
<tr>
<td>$20^\circ$ - $30^\circ$</td>
<td>$9.7 \pm 0.6$</td>
</tr>
<tr>
<td>$30^\circ$ - $40^\circ$</td>
<td>$7.7 \pm 0.4$</td>
</tr>
<tr>
<td>$40^\circ$ - $50^\circ$</td>
<td>$6.6 \pm 0.5$</td>
</tr>
<tr>
<td>$50^\circ$ - $60^\circ$</td>
<td>$6.3 \pm 0.5$</td>
</tr>
<tr>
<td>$60^\circ$ - $70^\circ$</td>
<td>$4.9 \pm 0.4$</td>
</tr>
<tr>
<td>$70^\circ$ - $80^\circ$</td>
<td>$4.4 \pm 0.3$</td>
</tr>
<tr>
<td>$80^\circ$ - $90^\circ$</td>
<td>$4.6 \pm 0.3$</td>
</tr>
<tr>
<td>$90^\circ$ - $100^\circ$</td>
<td>$4.4 \pm 0.3$</td>
</tr>
<tr>
<td>$100^\circ$ - $110^\circ$</td>
<td>$4.4 \pm 0.3$</td>
</tr>
<tr>
<td>$110^\circ$ - $120^\circ$</td>
<td>$5.2 \pm 0.3$</td>
</tr>
<tr>
<td>$120^\circ$ - $130^\circ$</td>
<td>$5.4 \pm 0.3$</td>
</tr>
<tr>
<td>$130^\circ$ - $140^\circ$</td>
<td>$6.5 \pm 0.4$</td>
</tr>
<tr>
<td>$140^\circ$ - $150^\circ$</td>
<td>$7.1 \pm 0.3$</td>
</tr>
<tr>
<td>$150^\circ$ - $160^\circ$</td>
<td>$9.5 \pm 0.4$</td>
</tr>
<tr>
<td>$160^\circ$ - $170^\circ$</td>
<td>$11.9 \pm 0.5$</td>
</tr>
<tr>
<td>$170^\circ$ - $180^\circ$</td>
<td>$12.9 \pm 1.0$</td>
</tr>
</tbody>
</table>
Fig. 3 Combined Results of the Three Runs
In Fig. 3 the results of Hadley et al.\textsuperscript{11} Wallace,\textsuperscript{12} and Fox,\textsuperscript{13} and recent counter works at Berkeley\textsuperscript{17} and Oxford\textsuperscript{18} are also plotted for the purpose of comparison. The neutron energy of the Oxford experiment was $105 \pm 3$ Mev. The results of the present experiment lie between those of Hadley et al and those of Fox in the large neutron-angle region, and agree very well with those of Chamberlain and Easley\textsuperscript{17} and of Wilson\textsuperscript{18} in the small neutron-angle region. These results manifested two general features: (a) the small value $(-3)$ of the observed isotropy ratio

$$ I = \frac{\sigma(\pi)}{\sigma(\frac{\pi}{2})}, $$

(b) a symmetry of the differential n-p scattering cross section about $90^\circ$ in the center-of-mass system.

These two features are the evidence for an interaction between nucleons of the form\textsuperscript{19,20}

$$ V = \frac{1}{2} \left(1 + P\right) J \{ r, \sigma_1, \sigma_2 \}, $$

where P is the space exchange operator. This interaction, in which ordinary and exchange forces enter with equal weight, is often referred to in the current literature as the Serber force. Calculations based on this Serber interaction of the angular distribution of the differential cross section and the total cross section at $90$ Mev were reported to be in good agreement with experiment.\textsuperscript{9}

At the present moment, the situation is rather discordant. The exchange forces were introduced primarily to explain the saturation of nuclear binding energies and nuclear densities. However, the Serber interaction with exchange force of the best fit does not lead to saturation. The Serber force has the property that all terms corresponding to odd orbital angular-momentum quantum numbers vanish. But these terms are precisely those which lead to a strong repulsion at short distances, and, therefore, are required for the saturation of nuclear forces. It has been shown\textsuperscript{20} that there is no saturation for an attractive Serber force.

An interaction consisting of a strong short-range repulsion surrounded by an attractive well has been suggested toward a solution of this theoretical dilemma.\textsuperscript{22} However, it was pointed out\textsuperscript{23} that a short-range repulsion is not an adequate substitute for an exchange interaction. The most likely inference at the present moment is that many-body forces cannot be neglected in heavy nuclei.\textsuperscript{20,24}
III. EXPERIMENTAL PROCEDURES

3.1 Neutron Beam

The 90-Mev neutrons used in this experiment were produced by bombarding a half-inch beryllium target with 190-Mev deuterons. The deuteron is a very loosely bound structure in which the neutron and proton actually spend most of their time outside the range of their mutual forces. Therefore, when a deuteron traverses the target, it is not improbable that the proton will strike one of the target nuclei and be effectively stripped off instantaneously, while the neutron remains outside the nucleus and continues its flight with the momentum it had at the instant of collision. This momentum consists of two parts. The first part, \( p_0 \), is attributable to the kinetic energy \( E_d \) of the center of mass of the deuteron and is

\[
p_0 = (M \ E_d)^{1/2}
\]

where \( M \) is the approximate neutron or proton mass. The second part, \( p_1 \), is due to the internal motion of the neutron relative to the center of mass of the deuteron. This internal momentum of the neutron is of the order

\[
p_1 \approx (M \ \epsilon_d)^{1/2}
\]

where \( \epsilon_d = 2.18 \) Mev is the binding energy of the deuteron. The energies of the stripped neutrons are within the limits given by

\[
E = \left(\frac{p_0 \pm p_1}{2M}\right)^2 \approx \frac{1}{2} E_d \pm (\epsilon_d \ E_d)^{1/2}
\]

A more detailed and accurate calculation\(^{14}\) shows that the full width at half maximum is

\[
\Delta E = 1.5 \ (\epsilon_d \ E_d)^{1/2} \approx 30 \text{ Mev}
\]

for \( E_d = 190 \) Mev.
The neutron energy spectra obtained in this experiment agree very well with this theoretical picture. Their full widths at half maximum were found to be approximately 30 Mev, as was predicted. With such a neutron energy spread, it is apparent that the differential n-p scattering cross section obtained in this experiment is in a sense an average value over an energy spread, and is not the cross section for monoenergetic neutrons at 90 Mev as the title indicates.

3.2 Collimation System

The locations in the cyclotron of the target, the collimation system and the cloud chamber are shown in Fig. 4. (This sketch is actually an earlier version and is used here only to avoid redrawing.) The collimation system in this experiment consisted of three collimators. The first collimator was located between the cyclotron tank and the concrete shielding. The second collimator was built in the neutron port in the concrete shielding. These two collimators are not shown in the figure. The third collimator was between the neutron port and the cloud chamber, as is shown in the figure. Table IV gives the dimensions of the collimators.

Table IV
Dimensions of the Collimators

<table>
<thead>
<tr>
<th></th>
<th>Length</th>
<th>Cross-sectional shape</th>
<th>Cross-sectional dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Collimator</td>
<td>72 inches</td>
<td>circular</td>
<td>2 inches</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>diameter</td>
</tr>
<tr>
<td>Second Collimator</td>
<td>34 inches</td>
<td>rectangular</td>
<td>$\frac{23''}{32} \times 2\frac{3''}{8}$</td>
</tr>
<tr>
<td>Third Collimator</td>
<td>30 inches</td>
<td>rectangular</td>
<td>1'' x 3''</td>
</tr>
</tbody>
</table>
Fig. 4 Locations of the Target in the Cyclotron Collimation System and Cloud Chamber
The angular spread of the neutron beam was determined by the dimensions of the third collimator. Since the end of the collimation system was about 65 feet from the beryllium target, the maximum angular deviation in the neutron beam was about $0.1^\circ$ from the central line.

3.3 The Cloud Chamber

Emerging from the collimator, the neutron beam was directed into a 22-inch pantograph cloud chamber through a 3-by-1-inch aluminum window 5 mils thick. The beam was then allowed to pass out through a similar window at the far end of the chamber in order to reduce secondary neutrons scattered back from the rear wall. The bottom of the chamber consisted of a rubber-covered half-inch-thick lucite disk which moved vertically, and was controlled by a pantograph which kept it accurately horizontal during the expansions. The disk was covered with gelatin with black dye dissolved in it. On the upper surface of the top glass of the chamber a black ring was painted with outer diameter equal to that of the chamber and with inner diameter of 17.5 inches, so that from the stereoscopic camera (described later) only the black bottom of the chamber could be seen. This black ring on the top glass, together with the black gelatin in the bottom of the chamber, furnished a perfectly black background for the tracks.

3.4 Operation

The chamber was operated in a pulsed magnetic field. This magnetic field was supplied by an electromagnet which, when its coils carry a current of 4100 amperes, produces a field of 22,000 gauss at the center of the chamber. The current in the magnet coils was supplied by a 150 hp mine-sweeper generator. The field took about 2.5 seconds to build up to its maximum value, where it remained steady for about 0.15 second before being turned off. During this interval (0.15 sec.) of steady maximum field, the operation of the chamber took place. The sequence of operation was as follows:

(a) The clearing field was shorted off.
(b) The chamber started suddenly to expand.
(c) The moving disk reached the bottom of the chamber.
(d) The first cyclotron pulse was sent into the chamber.
(e) Second neutron pulse.
(f) Third neutron pulse.
(g) The lights were flashed.

Table V gives the time intervals between the steps of the above sequence.

<table>
<thead>
<tr>
<th>Time intervals</th>
<th>First Run</th>
<th>Second Run</th>
<th>Third Run</th>
</tr>
</thead>
<tbody>
<tr>
<td>between (a) and (b)</td>
<td>~ 0.05 sec.</td>
<td>~ 0.05 sec.</td>
<td>~ 0.05 sec.</td>
</tr>
<tr>
<td>between (b) and (c)</td>
<td>~ 0.05 sec.</td>
<td>~ 0.05 sec.</td>
<td>~ 0.05 sec.</td>
</tr>
<tr>
<td>between (c) and (d)</td>
<td>0.001 sec.</td>
<td>0.001 sec.</td>
<td>0.001 sec.</td>
</tr>
<tr>
<td>between (d) and (e)</td>
<td>0.0016 sec.</td>
<td>0.0016 sec.</td>
<td>0.0016 sec.</td>
</tr>
<tr>
<td>between (e) and (f)</td>
<td>0.0016 sec.</td>
<td>0.0016 sec.</td>
<td>0.0016 sec.</td>
</tr>
<tr>
<td>between (d) and (g)</td>
<td>0.030 sec.</td>
<td>0.030 sec.</td>
<td>0.025 sec.</td>
</tr>
</tbody>
</table>

The clearing field was 400 volts in the first and the second runs, and was 150 volts in the third run.
3.5 Photography

The cloud chamber was illuminated through its lucite wall by a pair of General Electric F T 422 flash tubes, connected across 256-microfarad condenser banks charged to 1700 volts. A stereoscopic camera was mounted on a lighttight dome 27 inches above the top glass of the chamber. A pair of Leica Summitar 50 mm lenses at f6.3 were used in the camera. Figure 5 shows the location of the chamber, the camera and the lights. The pictures were taken on Eastman Linograph Ortho film in 100-foot strips 1.8 inches wide. Since the camera had no shutter, the length of exposure was determined simply by the length of the flash, which was about 100 microseconds.
Fig. 5  Locations of Camera, Lights, and Chamber
IV. MEASUREMENTS AND REDUCTION OF DATA

4.1 Reprojection Apparatus

Life-size reprojection of the photographs was effected by means of a double projector. Figure 6 shows the schematic drawing of this apparatus. The transparent screen of this projector has three translational degrees of freedom to locate the position of starting point of each track. The screen has also two rotational degrees of freedom to determine the direction of the tangent to the track at the starting point.

4.2 Details of Measurement

The following five quantities were measured for each track by means of the above-mentioned projector:

(a) The slant radius of curvature \( p' \), or the range \( R \) if the track ends in the illuminated region of the chamber.
(b) Dip angle \( \alpha \) -- the angle between the tangent to the track at the starting point and the horizontal plane.
(c) Beam angle \( \beta \) -- the angle between the projection of this tangent upon the horizontal plane and the direction of the incident neutron beam.
(d) The height \( h \) of the center of the track from the bottom of the chamber.
(e) The distance \( d \) between the center of the track and the central axis of the chamber.

The slant radius of curvature was determined by comparing the track with a series of circular arcs ruled on lucite templates. The zero point of the beam angle was obtained by setting the pointer on the beam angle scale just opposite the 0° mark when the fine line on the viewing screen coincided with the superimposed images of the five crosses on the top glass which indicated the beam direction. The zero point of the dip angle was obtained by adjusting the mirror in such a way that, for each of the five crosses, the two images could be brought into coincidence when the viewing screen was horizontal.
Fig. 6 Reprojection Apparatus
4.3 Acceptance Criteria

(a) Spatial Limitation. The acceptable region in the cloud chamber was determined primarily by the dimensions of the third collimator. Vertically this region was 1 inch high, lying between the distances of 1.25 inches and 2.25 inches from the chamber bottom. Horizontally, the region was 3 inches wide, 1.5 inches each way from the central line. This rectangular region was cut off by two vertical planes perpendicular to the beam direction through the end crosses, which were 12 inches apart. In other words, the dimensions of this region were 1 in. by 3 in. by 12 in. A track had to start inside this region to be acceptable, but it might end outside.

(b) Radius-of-curvature limitation. In order to limit our measurements to protons scattered by neutrons with energies greater than 40 Mev, it was necessary to determine a minimum acceptable slant radius of curvature. We have

\[ B \rho' \cos \alpha = \frac{10^4}{3} \left[ \frac{E_p}{E_p + 1876} \right]^{1/2} \]

where \( E_p \) is proton kinetic energy in Mev, \( B \) is magnetic field in gauss, and \( \rho' \) is in cm. Neglecting \( E_p \) in comparison with 1876, and setting \( E_p = E_n \cos^2 \theta = E_n \cos^2 \alpha \cos^2 \beta \), the above equation reduces to

\[ \rho' = \frac{10^4}{3B} \left( 1876 E_n \right)^{1/2} \cos \beta \]

where \( E_n \) is the neutron kinetic energy. By assuming \( E_n = 40 \) Mev (lower limit for neutron energy) and \( B = 21,700 \) gauss (average magnetic field), one obtains

\[ \rho' = \frac{10^4}{3 \times 21700} \left( 1876 \times 40 \right)^{1/2} \cos \beta \text{ cm} \]

depending on beam angle \( \beta \). This was the minimum acceptable slant radius of curvature.
In actual measurements, a track was measured and recorded if 
\[ \rho' \geq 40 \cos \beta \text{ cm.} \] A detailed table of \( \rho' \) vs. \( \beta \) according to the equation 
\[ \rho' = 40 \cos \beta \] was constructed for reference during the measurements. These measurements included a portion of proton tracks scattered by neutrons of energies below 40 Mev, which were discarded after the calculation.

(c) Dip-Angle Limitation. Because of the difficulties in measuring the curvature and the range of a track for large dip angles, the measurements were limited to regions where \( \alpha \) was less than a certain value \( \alpha_0 \). In this experiment, \( \alpha_0 \) was set at 40°.

Owing to this limitation of the dip angle \( \alpha \), the number of tracks observed was less than the number that would have been observed if the limitations were removed. Accordingly a weighting factor \( f \) should be applied to each track in order to give a correct weighted number. Assuming the tracks are azimuthally symmetrical, it can be easily shown that

\[ f = \frac{\pi/2}{\sin^{-1}\left(\frac{\sin \alpha_0}{\sin \theta}\right)}, \text{ for } \theta > \alpha_0; \]

\[ f = 1, \text{ for } 0 \leq \alpha_0, \]

where \( \theta \) is the angle between the initial proton track direction and the neutron beam.

4.4 Details of Calculation

(a) Proton energy determination. The energy of a proton track was determined by \( Bp \) for high energies and by the range \( R \) for low energies if the track stopped in the illuminated region of the chamber.

The magnetic field was determined by the current \( i \) in the magnet coils, which was recorded for every expansion during the run, and the \( h \) and \( d \) values described in section (4.2). Given \( i, h \) and \( d \), the magnetic field \( B \) was readily obtained from previously established tables. The value of \( Bp \) was simply \( Bp' \cos \alpha \).
The determination of the energy of a proton from its $B_p$ value was greatly facilitated by the use of a nomograph shown in Fig. 7. The determination of proton energy from its range is discussed in Section (4.5).

(b) Scatter angle determination. The scatter angle $\theta$ of a proton track in the laboratory system was determined by the relation

$$\cos \theta = \cos \alpha \cos \beta .$$

Two linear log cosine scales, similar to those of a sliderule but in an enlarged magnitude, were constructed to facilitate the computation.

(c) Neutron energy determination. The neutron energy $E_n$ is related to proton energy $E_p$ by the equation

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

(d) Azimuthal angle determination. The azimuthal angle $\phi$ is the angle between the horizontal plane and the projection of the tangent to the track at the starting point upon a plane perpendicular to the neutron beam. It can easily be shown from geometrical considerations that

$$\tan \phi = \tan \alpha \csc \beta .$$

The angle $\phi$ ranges from $0^\circ$ to $360^\circ$. The following table shows the value of azimuthal angle for different sign combinations of $\alpha$ and $\beta$.

<table>
<thead>
<tr>
<th>Sign of $\alpha$</th>
<th>Sign of $\beta$</th>
<th>Azimuthal Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>+</td>
<td>$\phi$</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>$180^\circ - \phi$</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>$180^\circ + \phi$</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>$360^\circ - \phi$</td>
</tr>
</tbody>
</table>

The computation was greatly facilitated by the use of two specially constructed linear scales, one in log tangent and the other in log cosecant. The nomograph shown in Fig. 8 was also very useful in the computation.
$B_p = \frac{10^4}{3} \left[ E_p (E_p + 1876) \right]^{\frac{1}{2}}$ for protons

Multiply number on top side of scale by $10^6$ to get $B_p$ in Gauss-cm. Bottom number gives $T$ in MeV.

Fig. 7 $B_p - E_p$ Relation
Fig. 8. Determination of $\phi$ by $\alpha$ and $\beta$. 
4.5 Range-energy relation

In order to determine energy of a proton from its range for low energies, a range-energy curve was constructed using Bethe's estimates of the range-energy relation for protons in air under standard conditions and Crenshaw's values of stopping powers of hydrogen relative to air as a function of incident proton energies. The range-energy relation curve shown in Fig. 9, originally computed for the first run, was also used for the third run, since the chamber pressures were practically the same in the two runs, 89.7 and 89.3 cm Hg respectively. The range-energy curve for the second run is shown in Fig. 10, in which the weighted stopping power of methane and hydrogen was used. Bethe's values agree essentially with other work.
Fig. 9. Range-Energy Relation for the First and the Third Runs
Fig. 10. Range-Energy Relation for the Second Run
V. DISCUSSION OF ERRORS

5.1 Errors in Energy Determination

In the previous papers\textsuperscript{10,29} of the Cloud Chamber Group program of the University of California Radiation Laboratory, it was shown that the approximate expression for the probable fractional error in neutron energy can be written as follows:

\[ \frac{\Delta E_n}{E_n} = 2 \times 0.67 \left[ \left( \frac{\Delta B}{B} \right)^2 + (2 \tan \alpha \Delta \alpha)^2 + \left( \tan \beta \Delta B \right)^2 + \left( \frac{0.08 \rho'}{L^2} \right)^2 + \left( \frac{\rho'}{\rho_t} \right)^2 \right]^{1/2} \]

where \( L \) is the length of chord of a track measured and \( \rho_t \) is the radius of curvature due to turbulence, other symbols having been defined previously. In deriving this expression, a resolving power of 0.01 cm in comparing the sagittas of the curves was assumed. The error given in the above expression originated from the following sources:

(a) Magnetic field measurement. \( \frac{\Delta B}{B} \) was about \( \pm 1.1/2 \) percent.

This included the radial variation of the field and small errors in reading the ammeter.
(b) Dip angle measurement. The estimate of the error in angle measurement was based on the reproducibility of the measurements. For dip angles less than 40°, it was found that \( \Delta \alpha = \pm 1.5^\circ = \pm 0.026 \) radians. The second term in the above expression depends on dip angle \( \alpha \), which ranges from 0° to 40°. For a representative track of dip angle of, say, 20°, this term is \( 2 \tan \alpha \Delta \alpha = \pm 2 \tan 20^\circ \times 0.026 = \pm 0.019 \), or about ± 2 percent.

(c) Beam angle measurement. Beam angle measurement was reproducible to 0.5°, or \( \Delta \beta = \pm 0.5^\circ = \pm 0.0087 \) radians. The angle ranged from 0° to 86°. For a representative track of beam angle of, say, 45°, the third term in the error expression is \( \tan \beta \Delta \beta = \pm 0.0087 \), which is less than ± 1 percent.

(d) Template matching. Aside from the resolving power of the human eyes, the error in matching a circular arc on the lucite template with the track depended upon the energy of the neutron and the length of the track. Consider a representative track, for which \( \beta = 45^\circ \) and \( E_n = 90 \text{ Mev} \). For this track

\[
\rho' = \frac{10^4}{3B} \left( 1876 \ E_n \right)^{1/2} \cos \beta = \frac{10^4}{3 \times 21700} \left( 1876 \times 90 \right)^{1/2} \cos 45^\circ = 44.5 \text{ cm}.
\]

Assuming \( L = 12 \) cm for this track, one gets for the fourth term in the error expression

\[
\pm \frac{0.08 \rho'}{L^2} = \pm \frac{0.08 \times 44.5}{(12)^2} = \pm 0.025,
\]

or about ± 2\(1/2\) percent.

(e) Turbulence. The temperature control system in this experiment was improved to give minimum turbulence. One picture in ten was taken without the magnetic field. The effect of turbulence was carefully studied by measuring the curvature of these "no field" tracks with a precision traveling microscope. All these tracks measured were found to have radii greater than 36 meters, except two tracks which had \( \rho_t = 25 \) meters. Positive and negative signs were found to occur with equal frequency. Using \( \rho_t = 3600 \) cm, one gets

\[
\frac{\rho'}{\rho_t} = \frac{44.5}{3600} = 0.012,
\]

or about ± 1 percent.
Putting these values of fractional errors due to the above five sources into the error expression given at the beginning of this section, one obtains about ± 5 percent as the fractional error in neutron energy determination. This was in a sense an average value. For large beam angles, the error became large, as can be seen from the third term of the error expression. This resulted in the broader spread of the neutron energy spectrum from the wide-angle proton group.

5.2 Errors in Cross-Section Determination

The main sources of error in cross-section determination were the following:

(a) **Missing tracks.** A total of 1738 tracks was measured from pictures of the first (1951) run. The process of measurement and checking was as follows. The tracks were first measured independently by two observers. Both observers had spent several months in making independent measurements. In comparing the two sets of measurements, it was noted that while 98 tracks were overlooked by the first observer, 75 tracks were missed by the second observer. All the pictures were checked again (a third time) in the projector. Six new tracks were discovered and measured. In checking the pictures the fourth time, no new tracks were discovered. It was estimated that the error due to missing tracks in the first run was not greater than 1 percent. This conclusion was further justified by the fact that the neutron energy spectra obtained from the two scatter-angle groups agreed remarkably with each other and with the theoretical picture, except for a slightly different spread in energies explained by errors in measuring large beam angles.

The pictures of the second (1952) run and of the third (1953) run were much clearer than those of the first run, and each picture contained much fewer tracks. The tracks in these pictures were so obvious at the first glance that they were very unlikely to be missed by an experienced observer in careful measurements. A portion of pictures of the second and the third runs containing 200 tracks were randomly picked and measured by an independent observer. No new tracks were discovered. The error due to missing tracks was estimated to be not greater than 1 percent.
(b) **Background neutrons.** Proton recoils caused by background or secondary neutrons could be estimated by counting the number of protons with scatter angle greater than $90^\circ$ in the laboratory system, since these protons were necessarily scattered by background neutrons. A portion of pictures containing 180 tracks was found to contain 2 proton recoils with scatter angle greater than $90^\circ$ within the acceptable region in the chamber. The error due to this source was therefore estimated to be about 1 percent.

(c) **Oxygen stars.** 2-prong oxygen stars consisting of a proton track associated with a very short recoil nucleus might be confused with protons scattered by neutrons. A separate investigation was previously carried out of a set of pictures taken with a cloud chamber filled with helium and oxygen. Two proton tracks were found among 500 stars in these pictures. It was estimated that about 1 percent of oxygen stars were 2-prong stars consisting of a proton track and a very short recoil nucleus. In this experiment the chamber contained about 2 percent of water vapor. Since the neutron cross section for oxygen was about ten times that for hydrogen, there were about 20 oxygen stars in 100 scattered protons. Only 1 percent of these stars might be confused with proton tracks. In other words, in every 100 scattered protons, only 0.2 star consisted of a proton and a very short recoil nucleus. The error due to this source was definitely less than 0.2 percent, and therefore completely negligible.

The error due to the above three sources was therefore estimated to be not greater than 2 percent. In addition to this there were the statistical errors, which were indicated in the results.
ACKNOWLEDGMENTS

The writer wishes to express his sincere gratitude to Professor Wilson M. Powell, who suggested the experiment and designed the chamber and the magnet. His continued interest and advice throughout the program and his active participation in this work have made this essentially complex experiment a success.

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This work was performed under the auspices of the Atomic Energy Commission.
A. Derivation of Geometrical Formulae

Let \( \mathbf{r}_0 \) be a unit vector along the tangent to the track at the starting point, \( \mathbf{t} \) be a unit vector along the neutron beam direction, \( \mathbf{j} \) be a unit vector perpendicular to \( \mathbf{t} \) in the horizontal plane, and \( \mathbf{k} \) be a unit vector along the vertical direction such that \( \mathbf{k} = \mathbf{t} \times \mathbf{j} \), as shown in the figure.
From the figure, we have
\[ r_0 = i \cos \alpha \cos \beta + j \cos \alpha \sin \beta + k \sin \alpha, \]
\[ r_0 = i \cos \theta + j \sin \theta \cos \phi + k \sin \theta \sin \phi. \]

By equating the corresponding components, we obtain the following formulae:

\[ \cos \theta = \cos \alpha \cos \beta \quad \text{(1)} \]
\[ \sin \alpha = \sin \theta \sin \phi \quad \text{(2)} \]
\[ \cos \alpha \sin \beta = \sin \theta \cos \phi \quad \text{(3)} \]

Dividing Equation (2) by Equation (3), one gets
\[ \tan \phi = \tan \alpha \csc \beta \quad \text{(4)} \]
In actual measurements the dip angles were limited to a certain maximum value $\alpha_0$ such that $0 \leq \alpha \leq \alpha_0$. Therefore, for $\theta > \alpha_0$, the azimuthal angles were limited to a maximum value $\phi_0$ such that $0 \leq \phi \leq \phi_0$. From Equation (2), we have

$$\phi_0 = \sin^{-1}\left(\frac{\sin \alpha_0}{\sin \theta}\right).$$

Assuming the distribution of tracks to be azimuthally symmetrical, the weighting factor, from the figure, is

$$f = \frac{2\pi}{4\phi_0} = \frac{\pi/2}{\sin^{-1}\left(\frac{\sin \alpha_0}{\sin \theta}\right)}, \text{ for } \theta > \alpha_0.$$
C. Remarks on Computation of Cross Sections

In computing the cross sections for the five-degree angular group in the laboratory system, there are two approaches. Method I: Obtain the cross section in the usual way for the entire group. Method II: Subdivide the five-degree group into five one-degree subgroups, obtain the cross sections in the usual way for the five subgroups, and take the average value. There are no significant differences in absolute cross sections by these two methods except that Method II gives a slightly higher value at extreme angles. The value obtained by Method II, as Professor Wilson M. Powell has pointed out, gives the cross section at the middle point of the group.
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