Measurement of Neutron Differential Cross Sections Using the Associated Particle Method

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MEASUREMENT OF NEUTRON
DIFFERENTIAL CROSS SECTIONS
USING THE ASSOCIATED PARTICLE METHOD

by

Gary Eugene Rochau

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment
of the
Degree of Master of Arts

Western Michigan University
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Also, I would like to thank Mr. R. Durbin for the use of the shop facilities in the construction of the apparatus, and to Mr. M.E. Warren for his help with the computer and electronics.

Finally, I would like to thank my wife, Kathleen, for the many hours of patience and work she has had to endure during the course of this work.

Gary Eugene Rochau
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>4</td>
</tr>
<tr>
<td>A. The D(d,n)(^3)He Reaction</td>
<td>4</td>
</tr>
<tr>
<td>B. Scattering Chamber</td>
<td>9</td>
</tr>
<tr>
<td>C. Foil Targets</td>
<td>18</td>
</tr>
<tr>
<td>D. Associated Particle Detector</td>
<td>21</td>
</tr>
<tr>
<td>E. Sample Stand</td>
<td>26</td>
</tr>
<tr>
<td>F. Neutron Detectors</td>
<td>26</td>
</tr>
<tr>
<td>G. Electronics</td>
<td>34</td>
</tr>
<tr>
<td>H. Target Deterioration</td>
<td>40</td>
</tr>
<tr>
<td>I. Neutron Beam Profile</td>
<td>41</td>
</tr>
<tr>
<td>J. Shielding</td>
<td>41</td>
</tr>
<tr>
<td>III</td>
<td>45</td>
</tr>
<tr>
<td>A. Procedure for Taking Data</td>
<td>45</td>
</tr>
<tr>
<td>B. Cross Section Calculation</td>
<td>47</td>
</tr>
<tr>
<td>C. Results and Discussion</td>
<td>50</td>
</tr>
<tr>
<td>IV</td>
<td>55</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>55</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>60</td>
</tr>
</tbody>
</table>
### FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Description</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Variation of Neutron and $^3\text{He}$ Energy</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Variation of Neutron and $^3\text{He}$ Angle</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>D($d$,n)$^3\text{He}$ Cross Section</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>Side View of Scattering Chamber</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>Top View of Scattering Chamber</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>Recoil Particle Energies</td>
<td>23</td>
</tr>
<tr>
<td>7</td>
<td>Recoil Particle Pulse Height Spectrum</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>Side View of Sample Stand</td>
<td>28</td>
</tr>
<tr>
<td>9</td>
<td>n-$\gamma$ Time Spectrum</td>
<td>31</td>
</tr>
<tr>
<td>10</td>
<td>Proton Recoil Spectrum</td>
<td>33</td>
</tr>
<tr>
<td>11</td>
<td>Electronics</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>$^3\text{He}$-n Coincidence Spectrums</td>
<td>39</td>
</tr>
<tr>
<td>13</td>
<td>Neutron Beam Profiles</td>
<td>43</td>
</tr>
<tr>
<td>14</td>
<td>$^{12}\text{C}(n,n)^{12}\text{C}$ Differential Cross Section</td>
<td>53</td>
</tr>
<tr>
<td>TABLE</td>
<td>DESCRIPTION</td>
<td>PAGE</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>I</td>
<td>THE ENERGIES AND ANGLES OF THE NEUTRONS EMITTED AT 90° CM FROM THE D(d,n)³He REACTION</td>
<td>12</td>
</tr>
<tr>
<td>II</td>
<td>ESTIMATES OF CROSS SECTION CORRECTION FOR ELASTIC SCATTERING OF 7.0 MeV NEUTRONS FROM CARBON</td>
<td>51</td>
</tr>
<tr>
<td>III</td>
<td>A COMPARISON OF THE EXPERIMENTAL PARAMETERS FOR THE APM AND THE PBM FOR THE MEASUREMENT OF THE ¹²C(n,n)¹²C DIFFERENTIAL CROSS SECTION</td>
<td>57</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

A common technique for the measurement of neutron energies is to determine the time required by the neutron to travel between two reference points. This technique, termed the time of flight method, is used to measure energies as low as a few millielectron volts (meV) for neutrons from nuclear reactors and up to a billion electron volts (GeV) for neutrons from large particle accelerators. The present work is concerned with the application of the time of flight method to measure neutron energies in the million electron volt (MeV) range. Neutrons in the MeV energy range are particularly useful for studying the properties of nuclei.

Two variations of the time of flight technique for the production of neutrons in the MeV energy range are the pulsed beam time of flight method (PBM) and the associated particle time of flight method (APM). For the PBM, the incident charged particle beam of the neutron producing reaction is pulsed and bunched into short bursts. This type of beam is characteristic of cyclotrons and can be artificially created by Van de Graaff machines. The two events which are utilized for the PBM to determine the flight time are the time at which the burst of charged particles passes a particular point in space and the time at which a neutron, resulting from this burst, strikes the neutron detector. The APM, however, utilizes the constant incident beam current of a Van de Graaff accelerator. Here, the time of detection of the associated recoil particle from the
neutron producing reaction is used as one event and the time of de-
tection of the neutron as the other. Both of these procedures are
described in detail by Neiler (Ne 60).

The APM has been used with the D(d,n)$^3$He and T(d,n)$^4$He reaction
for many years. However, until recently, deuteron energies of only
a few hundred kiloelectron volts (keV) have been employed. Thus,
the neutron energy has been limited to a range of 2 to 3 MeV for the
D(d,n)$^3$He reaction and near 14 MeV for the T(d,n)$^4$He reaction. Only
low energy deuterons were employed due to two major difficulties.
One difficulty was the large count rate caused by elastically scat-
tered deuterons. The second was the difficulty of separating the
$^3$He particles from other reaction products.

Recently, some of the problems encountered using the APM at
higher energies have been overcome. Schuster (Sc 69) was able to
solve the problem caused by the large number of deuteron counts by
using a very thin associated particle detector and fast electronic
techniques. Thus, collimated neutron beams were produced over the
neutron energy range 2 to 14 MeV by employing deuteron energies up to
14 MeV. His work was investigative in nature and proved that the APM
was possible for production of fast neutrons over a wide energy range.

Hagengruber (Ha 71) extended Schuster's work to the use of the
APM for measurement of neutron differential cross sections and neu-
tron polarizations. He found that differential cross sections could
be measured conveniently provided that small sample to detector dis-
tances and samples of relatively large cross section were utilized.
As a consequence of the small sample to detector distance, it was not possible, in his work, to resolve the elastically and inelastically scattered neutrons on the basis of their different flight times. The measurement of neutron polarizations was found to be impractical due to the extremely small flux of polarized neutrons available.

The object of the present work was to investigate the use of the APM for scattering experiments over the neutron energy range 5 to 10 MeV. This work differs from the experiment of Hagengruber in that larger sample to detector distances and a somewhat smaller total time spread were employed. The system was tested at 7 MeV by scattering neutrons from carbon.

The work presented here consists of a discussion of the apparatus used for the APM and the measurement of the $^{12}\text{C}(n,n)^{12}\text{C}$ angular distribution. The advantages and disadvantages of the technique are examined, also.
II. EXPERIMENTAL TECHNIQUE

A. The D(d,n)³He Reaction

Figures 1 and 2 show the energy and angle of the reaction products for the D(d,n)³He reaction as a function of incident deuteron energy. The parameters for these curves were generated using the relativistic kinematics code KINMAT. A neutron energy range of 2 to 16 MeV can be produced using deuteron energies up to 14 MeV. The associated ³He particles are confined to a cone which becomes smaller as the incident deuteron energy increases above 3.27 MeV. The maximum lab angle for the ³He particles is given by

\[ \theta_{\text{max}} \leq \sin^{-1}\left(\sqrt{1 + 6.54/E(\text{MeV})}\right) \]

Above \( E_d = 3.27 \text{ MeV} \) and for all angles \( \theta < \theta_{\text{max}} \), there are two neutron groups corresponding to the same ³He angle. The angle of each of these two groups is shown in Figure 2 for several incident deuteron energies. The higher energy neutron group corresponds to a lower energy ³He group. There are two reasons why the higher energy neutron group is difficult to use. One reason is that the lab angle for this neutron group is too small for performing measurements conveniently. The second reason is that the low energy ³He particles corresponding to this group have a high energy loss in the source target. Thus it is difficult to separate these ³He particles from the elastically scattered deuterons reaching the associated particle detector.

For differential cross section measurements it is desirable to have zero neutron polarization of the incident neutron beam. It is
Figure 1

Curves showing the variation of neutron and associated $^3\text{He}$ energy for the $D(d,n)^3\text{He}$ reaction as a function of neutron angle and incident deuteron energy. These curves were generated using a relativistic computer program.
Figure 2

Curves showing the variation of associated $^3\text{He}$ angle with neutron angle as a function of the incident deuteron energy for the D(d,n)$^3\text{He}$ reaction. A maximum occurs in the associated $^3\text{He}$ angle for deuteron energies above 3.27 MeV.
well known that neutrons from the $D(d,n)^3$He reaction have large polarizations at many emission angles (Ba 65). At $\theta_{CM} = 90^\circ$, however, the polarization of the outgoing neutrons is zero at all incident energies as a result of the symmetry of the reaction. To eliminate the need for polarization corrections, data were taken at $\theta_{CM} = 90^\circ$.

It is advantageous when measuring differential cross sections to have the incident flux of neutrons as large as possible. Figure 3 shows the differential cross section for the $D(d,n)^3$He reaction (Sc 69). For a deuteron energy of 10 MeV, the neutron lab angle corresponding to $90^\circ_{CM}$ is $66^\circ$. This neutron angle is very near a maximum in the $D(d,n)^3$He cross section.

For a maximum deuteron energy of 14 MeV, using the neutron beam at $90^\circ_{CM}$ limits the maximum neutron energy of the APM to 9.45 MeV. The neutron yield is determined by the maximum beam intensity and maximum usable foil thickness. Table I lists the kinematic parameters for the unpolarized neutrons at $90^\circ_{CM}$ as a function of deuteron energy.

**B. Scattering Chamber**

A side view and a top view of the scattering chamber are given in Figures 4 and 5, respectively. The chamber was constructed of a 3½ quart stainless steel mixing bowl\(^1\) which was 21.6 cm in diameter, 10.8 cm deep and had a 0.05 cm wall thickness. The bowl was fitted with three 2.54 cm diameter stainless steel tubes. Two of the tubes

\(^1\)Supplied by West Bend Company, West Bend, Wisconsin.
Figure 3

The D(d,n)$^3$He cross section as a function of neutron laboratory angle for $E_d = 10$ MeV. The cross sections for elastic scattering of deuterons from typical target materials is plotted as a function of the associated particle angle associated with each neutron angle for the D(d,n)$^3$He reaction.
11

ASSOCIATED $^3$He ANGLE

$E_d = 10$ MeV

CROSS SECTION (mb/sr)

$D(d,d)D$

$^{12}C(d,d)^{12}C$

$D(d,n)^3$He

X10

NEUTRON ANGLE
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</tr>
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</table>

*) All quantities are in the laboratory system.
Figure 4

A side view of the scattering chamber. The chamber is shown with the wobbling mechanism attached. For clarity, the plane of the target holder is shown as being in the plane of the paper.
Figure 5

A top view of the scattering chamber showing sample stand and neutron detector with shielding.
were optically aligned to serve as entrance and exit ports for the deuteron beam. The third was situated at 45° to the entrance port to serve as a viewing port. The top of the bowl was fitted with a 0.635 cm thick aluminum lid. The center of the chamber's flat bottom was fitted with an aluminum plug. This plug served as a center reference point for the chamber. It also served as a point to which a 0.2 cm thick aluminum plate could be attached to prevent the collapse of the chamber bottom while under vacuum.

A tantalum beam defining collimator mounted on an insulated stainless steel bellows was located 20 cm in front of the source target. The collimator, rectangular in shape, was 0.16 cm wide by 0.635 cm high. The shape of the collimator was such as to spread the beam intensity over the target without affecting the scattering geometry appreciably. The incident beam was stopped by a tantalum disc 5.1 cm in diameter, located 1.5 meters from the source target.

The associated particle detector was mounted in a holder which could be moved radially along the chamber lid. The holder contained a defining collimator and an antiscattering baffle as well as the detector. The position of the detector was determined by a zero degree reference mark on the chamber, and graduations on the chamber lid. The lid was graduated in 1° increments, and the detector position was changed by rotating the chamber lid.

Source targets were wobbled horizontally to spread heating by the incident beam. The wobbling mechanism consisted of a teflon cam moving a 0.65 cm diameter stainless steel tube. The targets were constrained to move in a vertical plane by a pivot consisting of a
set of needle bearings. The targets were wobbled at 2 Hz by a 120 rpm alternating current induction motor. A direct current motor was also tested. However, the brush contacts of the motor generated considerable radio frequency noise which was sensed by the electronics.

The angle between the targets and the beam was changed by rotating the entire wobbling mechanism. Three targets could be placed in the chamber simultaneously.

C. Foil Targets

Thin foils of deuterated polyethylene were used as targets for the D(d,n)$^3$He reaction. It is necessary that the targets be thin in order for the recoil $^3$He particles to emerge from the target without excessive energy loss. The $^3$He particles must be resolved in energy from the elastically scattered deuterons. Also, the energy spread of the $^3$He particles due to the target thickness degrades the coincidence time resolution. A 20 to 25 µm thick target was satisfactory for the experimental conditions of the present work.

The deuterated polyethylene foils were made by a method similar to that of Tripard and White (Tr 67). Deuterated polyethylene powder was dissolved in ortho-xylene at a temperature of 155°C. To overcome problems of superheating, 5 ml of xylene was placed in a 40 ml test tube and heated in a mineral oil bath. This technique provided steady heating of the xylene. Bumping of the xylene was

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$^2$Supplied by Prochem Ltd., P.O. Box 555, Lincoln Park, New Jersey.
eliminated by placing a square ended glass rod in the xylene and agitating the solution when it had reached 140°C until the boiling action was self-sustaining. When the oil bath reached 155°C the heat was removed and the desired amount of deuterated polyethylene powder added. Approximately 20 mg of powder would produce a foil 20 to 25 μm thick. When the temperature of the bath fell below 150°C the heat was reapplied until it again reached 155°C. It was necessary to boil the solution a second time since the powder was slow in dissolving and only when the xylene was boiling did the powder dissolve. Loss of xylene was minimal since the test tube was long enough that the xylene vapor condensed near the top of the tube.

The thickness of the foils produced by this method depended on the mass to volume ratio of the powder and xylene, and the procedure employed in the pouring of the solution. The solution of xylene and polyethylene at 150°C was poured onto a glass slide at room temperature. The glass slides were 5.1 cm x 5.1 cm x .1 cm lantern slides coated with Teepol<sup>3</sup>, a sodium sulfate based detergent. When pouring the solution, it was necessary to insure that all of the solution remained on the top surface of the slide and covered it uniformly in order to obtain consistent results. The slides were large enough so that the surface tension of the solution at the edges of the slide was sufficient to keep the volume of the solution on the top surface. It was necessary for the slides to dry for 24 hours, or until the xylene had evaporated. When the foil had set firmly, the desired

<sup>3</sup> Supplied by Shell Chemical, Houston, Texas.
size of foil was scored and floated off the lantern slide into distilled water. The exact angle of entry of the slide into the water was not important. The resultant foils were very durable and could be handled easily with a tweezers. The foils were then mounted on aluminum frames which had a 1.27 cm x 1.9 cm aperture.

The thicknesses of the deuterated polyethylene foils were determined by measuring the energy loss, in traversing the foil, of 5.48 MeV alpha particles from $^{241}\text{Am}$. The energy loss of $C_2D_4$ was obtained by first adding the energy loss for $C_2$ and $\text{H}_4$ using empirical formulas given by Whaling (Wa 58) and then changing the mass factors to correspond to $C_2D_4$. The energy loss of protons with energy greater than 1 MeV, in $C_2D_4$ is given by

$$\frac{dE}{dx} \text{ MeV} = \frac{18.05\rho}{E} \ln \frac{E^4}{216} + 20.14,$$

where $\rho$ is the density of the polyethylene in g/cm$^3$ and $E$ is the proton energy in MeV.

When a new foil was first used, it was necessary to condition the foil so that it would not crack along the edges of the holder. An intense beam placed on the target initially caused this breakage to occur. The problem was resolved by first using the target at a low beam current of approximately 75-100 na. After 90 minutes of continuous exposure the foil had stretched enough to allow higher beam currents of 150-200 na.
D. Associated Particle Detector

The associated $^3$He particles were detected in a totally depleted surface barrier detector $^4$ 50 $\mu$m thick. The use of this type of detector is desirable, since for the conditions of the present experiment, the elastically scattered deuterons do not stop in the detector. Thus, they deposit much less energy in the detector than the $^3$He particles which lose all of their energy. Figure 6 is a plot of the particle energy deposited in the detector as a function of the energy of the outgoing neutron for reaction products that can be obtained by bombarding deuterated polyethylene foils with deuterons.

Figure 7 shows the pulse height spectrum from the associated particle detector at a neutron energy of 7.0 MeV. The deuteron energy was 9.2 MeV and the $^3$He particle energy is 5.46 MeV at $37^\circ$. It was not possible in the present work to completely separate the $^3$He particles from all reaction products produced by the deuterated polyethylene target. Alpha particles from the $^{12}$C(d,$\alpha$)$^{10}$B reaction are a source of background of this type. The alpha groups from this and other competing reactions do not contribute significantly to the accidental coincidence rate since the cross sections for these reactions are small.

The totally depleted surface barrier detector suffers radiation damage with long exposure to a large flux of charged particles. Deterioration of the 50 $\mu$m detector could be observed as an increase

$^4$ Supplied by Nuclear Diodes, P.O. Box 135, Prairie View, Illinois.
Figure 6

The particle energy deposited in a 50 µm totally depleted surface barrier detector as a function of unpolarized neutron energy. The curves were calculated using the energy loss of each particular charged particle in silicon. The energy of each reaction product was kinematically calculated using the geometry and incident deuteron energy required for each unpolarized neutron energy.
Figure 7

The pulse height spectrum as measured by the totally depleted detector at an unpolarized neutron energy of 7.0 MeV. The detector is at 37° and the $^3\text{He}$ particle energy is 5.5 MeV. The shaded area shows the result of gating the spectrum by the $^3\text{He}$-n coincidences.
in the current supplied by the detector bias supply. During the course of this work, the detector leakage current increased from .55 μA to .95 μA.

E. Sample Stand

A separate stand, shown in Figures 5 and 8, was used to support the scattering sample and neutron detector. The stand was designed such that the axis of a cylindrical sample was the same as the vertical axis of the stand. The sample was suspended in the neutron beam by a thin walled stainless steel tube 0.63 cm in diameter. The neutron source to sample distance was determined using the neutron beam profile (see Section II I).

The neutron detector was mounted on the stand so that it could both rotate about the sample and move radially from the sample position. The position of the detector was determined by a reference mark and graduated ring on the sample stand.

Neutron scattering due to the apparatus was checked experimentally at forward angles. Tests performed for times comparable to experimental runs showed no events distinguishable from background.

F. Neutron Detectors

Three different types of scintillators were used in this work. For measurement of angular distributions, a glass cylinder 5.1 cm in diameter and 8.5 cm long filled with NE218\(^5\) liquid hydrogenous scin-

\(^5\)Supplied by Nuclear Enterprizes, 935 Terminal Way, San Carlos, California.
Figure 8

A side view of the sample stand.
tillator served as a neutron detector. For the measurement of the neutron beam profile, a 1.9 cm diameter 2.5 cm long stilbene crystal was used. The neutron monitor scintillator was a 5.1 x 5.1 x 2.5 cm block of NE102 plastic scintillator. Each scintillator was optically coupled to an RCA 8575 photomultiplier tube.

The outputs of the NE218 and stilbene detectors were supplied to a pulse shape discrimination system. This system separated neutron and gamma ray induced events in the scintillator. The light decay from the scintillator results from a combination of an intense fast decaying component and a less intense slow component. The slow component is more intense for a neutron induced event than one initiated by a gamma ray. This difference in decay times is then used by the pulse shape discrimination system to separate gamma rays from neutrons. A typical n-γ spectrum for 7 MeV incident neutrons is shown in Figure 9. This spectrum, generated by a time to amplitude converter, shows the elapsed time between the initiation and decay of a scintillation pulse. Since gamma ray induced events decay faster than neutron events, the gamma ray group occurs first in the time spectrum.

Neutrons are detected as proton recoils in the scintillator. A proton recoil spectrum, gated by the ³He- n coincidence and n-γ discrimination, is shown in Figure 10.

Figs. 1, 2, and 3 and Table I of this chapter were presented originally in ref. (Ha 71).

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\(^6\)ibid.
Figure 9

The n-γ spectrum at 7.0 MeV neutron energy produced using the NE218 scintillator. The relative magnitude and separation of the peaks is dependent upon the neutron and gamma fluxes and upon the particular electronic settings used. The arrows indicate the SCA acceptance window used to gate the $^3$He-n coincidences.
Figure 10

The proton recoil spectrum from the NE218 scintillator at 7.0 MeV neutron energy. This spectrum has been gated by the $^3\text{He}$-n coincidences and n-γ discrimination.
G. Electronics

Figure 11 is a block diagram of the electronics used for cross section measurements. A fast timing signal was created by a time pick-off unit inductively coupled to the output of the $^3$He detector. The time pick-off unit utilized leading edge discrimination to eliminate pulses from the associated particle detector due to elastically scattered deuterons. The output of the time pick-off unit was supplied to a fan-out buffer which then supplied timing signals to the stop inputs of the time to amplitude converters TAC1 and TAC3.

A second timing pulse was derived from the anode of the neutron detector. These signals were supplied to a constant fraction discriminator which was used for pulse shaping and signal fan-out only. One of the outputs of this unit was connected to the start input of TAC1. The output of TAC1 then represented the correlation in time of pulses from the neutron detector and the $^3$He detector, or the $^3$He-n coincidence spectrum. Because the neutron detector is also sensitive to gamma rays, the background in the $^3$He-n spectrum was large. This high background was eliminated by using pulse shape discrimination. The linear signal from the last dynode of the neutron detector was integrated and differentiated by a double delay line amplifier. This amplifier provided bipolar signals whose crossover points were different for neutrons than for gamma rays. The output of the double delay line amplifier was then connected to a timing single channel analyzer (TSCA). The TSCA provided a fast timing signal and also served as a low level discriminator or bias. The
Figure 11

A detailed schematic of the electronics used for the cross section measurements. The heavy lines carry fast timing signals.
output of the TSCA was presented to the stop input of TAC2. The start input of TAC2 was supplied by the anode signal of the neutron detector. In this manner the crossover time of gamma ray induced pulses could be measured with respect to that of the neutron pulses. Because the output of the time to amplitude converter is proportional to the time of crossover, a single channel analyzer (SCA) can be placed on the output of TAC2 to select the neutron group. The output of this SCA was then used to gate the output of TAC1.

Gating of the $^3\text{He}$-n spectrum by n-γ discrimination reduced the background. However, the reduction in background was not as dramatic in the incident neutron beam as when measuring the scattered neutron beam intensity. Without n-γ discrimination, reliable measurements of small neutron fluxes would be impossible.

A SCA was placed on the output of TAC1 to select the $^3\text{He}$-n coincidence peak. The output of this SCA was used to gate the linear signals of the $^3\text{He}$ and neutron detectors.

The neutron monitoring system did not utilize n-γ discrimination since the chance coincidence rate under the neutron peak represented less than 0.5% of the true coincidence rate.

Figure 12 shows typical coincidence spectrums for a neutron energy of 7.0 MeV. The observed 2.1 nsec timing resolution of the NE218 scintillator was due in part to the large dimensions of the scintillator. Using similar electronics with the smaller stilbene crystal produced a timing resolution of approximately 1.5 nsec.
Figure 12

$^3$He-n coincidence spectrums. The peaks represent correlations in time between neutrons and $^3$He particles. The spectrums are:

a) $^3$He-n coincidence with the detector in the neutron beam gated by n-γ discrimination. 
b) $^3$He-n coincidences for natural carbon at a scattering angle of 45° LAB. 
c) $^3$He-n coincidences for polyethylene at a scattering angle of 45° LAB.
H. Target Deterioration

Yield and deterioration tests were performed on polyethylene and deuterated polyethylene targets at various beam intensities. Polyethylene foils were first used to determine the range of usable beam currents. Targets were wobbled at 2 Hz with an incident beam of protons. The energy of the incident proton beam was selected to duplicate the energy loss conditions of a 9.6 MeV deuteron beam. The deterioration was measured by observing the change in flux of elastically scattered protons from hydrogen. The scattering angle was the same as the $^3$He angle required for unpolarized 7.25 MeV neutrons.

The deterioration of the neutron yield was measured for several beam currents and for several targets. The measured deterioration for a 26 μm polyethylene foil after one hour of bombardment was about 10% of the initial yield for a constant beam current of 100 na. Under constant exposure to a 200 na beam, the neutron yield from a deuterated polyethylene foil dropped approximately 20% in the first 30 minutes for targets 20 to 25 μm thick. After the first 30 minutes, the rate of deterioration was approximately 7% per hour.

Deterioration of the target can be attributed to beam heating. High beam currents, 500 to 800 na, can be tolerated for a period 1 to 2 minutes with equivalent times with the beam off of the target. Without wobbling of the target, destruction of the target was immediate for beam currents over 25 na.

Initial exposure of a fresh 20 to 25 μm thick target to a beam
of 200 na or larger shortened the life of the target considerably.
To achieve the best performance from a foil, it was necessary to
start using it with a 100 na beam for 90 minutes. After this period,
the target was usable for approximately 30 hours at 250 to 300 na.
Initial exposure of a foil to a very high beam current would cause
the foil to break away from its holder.

I. Neutron Beam Profile

Measured horizontal and vertical neutron beam profiles are
shown in Figure 13. The shape of the profile was determined by the
collimation geometry of the $^3$He detector and the incident beam. The
geometry used defined a rectangular beam 0.15 x 0.64 cm. The asso­
ciated particle detector was defined by a rectangular aperture 0.20
x 0.64 cm, 6.9 cm from the source target. The wings of the profile
are due to the finite size of the incident deuteron beam.

The coincidence rate at the center of the neutron beam compared
to the coincidence rate outside the beam was about 800:1. All counts
outside the neutron beam were caused by accidental coincidences.

J. Shielding

In principle, extensive use of shielding is not necessary with
the associated particle method. However, limited amounts of shiel­
ding are necessary when measuring small neutron fluxes. The source
reaction is the largest source of background. A block of iron ap­
proximately 20 cm long was the main shield between the neutron de­
Figure 13

The horizontal and vertical neutron beam profiles measured at $\theta_n = 66.5^\circ$ and $E_d = 9.2$ MeV, corresponding to an unpolarized neutron energy of 7.0 MeV. The measurements were made with the stilbene crystal mentioned in Section II F.
tector and the neutron source. Approximately 7 cm of paraffin between the detector and the source also helped suppress the background. Shielding of the beam defining collimator by iron was also beneficial. An iron shield was also used to shadow the beam stop from the detector. However, background from the beam stop was not significant for the geometry of the present work.
III. STUDY OF THE ELASTIC SCATTERING OF NEUTRONS FROM CARBON

A. Procedures for Taking Data

A collimated beam of unpolarized neutrons was produced using the associated particle method. A deuterated polyethylene target was bombarded with 9.2 MeV deuterons to produce a 7 MeV neutron beam. The emission angles in the laboratory system of the unpolarized neutrons and the associated $^3$He particles were 66.5° and 37°, respectively.

The neutrons were scattered from a cylindrical sample of natural carbon, 2.58 cm in diameter and 4.29 cm long. The sample was located 45.7 cm from the source target and positioned in the center of the neutron beam. The incident neutron energy spread was about 175 keV. The center of the neutron beam was determined by a previous measurement of the beam profile. The number of scattered neutrons was measured from 30° to 130° in 15° steps using the NE218 detector described in Chapter II. The sample and detector were separated by a distance of 44.5 cm. The contribution to the energy spread of the elastically scattered neutrons due to the angular width of the detector was about 100 keV. The size of the neutron detector was such that the height/diameter ratio was 1.66, the same ratio as that of the sample. The neutron flux incident upon the sample was measured by removing the carbon sample and placing the neutron detector in the direct beam at 0°.

For this measurement, the neutron detector was positioned in the neutron beam so as to subtend the same solid angle as the sample, i.e.,
the target to detector distance was determined as the product of the target to sample distance and the ratio of the detector diameter to the sample diameter.

A monitor detector was positioned 75 cm behind the scattering sample to measure the neutron-$^3$He coincidence yield during measurements of the scattered neutron flux. Since it was not possible to determine an accurate monitor flux while measuring the incident neutron flux, monitor data were measured before and after the incident flux measurements with the neutron detector out of the direct beam and the carbon sample in it. The scattered flux at each angle and the incident flux were normalized using the appropriate measured values of the monitor flux.

Each measured neutron flux was corrected for background. A background run taken with the sample out and with the neutron detector at $30^\circ$ indicated no time correlated background was present. Thus, it was possible to take foreground and background runs simultaneously in the following way. The gated output of TAC1 (see Figure 11) was supplied to an analog to digital convertor interfaced to a Digital Equipment Corporation PDP-15 computer. The programming of the computer was such that the peak of the coincidence spectrum could be integrated over a predetermined number of channels. The background under the peak was determined by integrating the remaining portion of the spectrum and obtaining an average over the same number of channels as in the peak summation. This background correction ranged from 20% at $30^\circ$ to 70% at $130^\circ$. 

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The procedure for taking data was to measure in turn the monitor flux, incident flux, monitor flux, scattered and monitor flux simultaneously, monitor flux, incidence flux, etc. The gated linear spectra of the $^3$He and neutron detectors were accumulated during the measurement of the incident flux as a check against bias and gain changes. Scalers were used to monitor counting rates, background, and bias changes, also.

B. Cross Section Calculation

For a small infinitely thin scattering sample, the laboratory differential cross section, $\sigma_L(\theta)$, can be obtained from the formula

$$\sigma_L(\theta) = \frac{F_S r^2}{F_I N},$$

where $F_S$ is the scattered flux (neutrons-cm$^{-2}$-sec$^{-1}$), $F_I$ is the flux incident upon the sample (neutrons-cm$^{-2}$-sec$^{-1}$), $r^2$ is the mean square distance from the sample to the detector, and $N$ is the total number of nuclei in the sample.

The incident neutron flux is given by

$$F_I = \frac{I_0'}{\Omega_S d^2},$$

where $I_0'$ is the number of neutrons/sec incident upon the sample, $\Omega_S$ is the solid angle of the sample, and $d$ is the target to sample distance. The scattered flux may be written as

$$F_S = \frac{I'(\theta)}{A_D} = \frac{I'(\theta)}{\Omega_D D^2},$$

where $I'(\theta)$ is the number of neutrons/sec incident upon the detector.
at angle $\theta$, $A_D$ is the cross sectional area of the detector, $\Omega_D$ is the solid angle of the detector, and $D$ is the source to detector distance while measuring the incident flux.

If $I(\theta)$ is defined as the number of neutrons counted by the detector at angle $\theta$ with the sample in, then $I'(\theta)$ is given by

$$I'(\theta) = \frac{I(\theta)}{\varepsilon(\theta)},$$

where $\varepsilon(\theta)$ is the efficiency of the neutron detector at angle $\theta$.

Similarly, if $I_o$ is the number of neutrons counted by the detector when measuring the incident flux, then $I_o'$ is given by

$$I_o' = \frac{I_o}{\varepsilon(0^\circ)},$$

where $\varepsilon(0^\circ)$ is the efficiency of the neutron detector when measuring the incident flux. Since $\Omega_S = \Omega_D$ for the present experiment,

$$F_S = \frac{I(\theta) \varepsilon(0^\circ) d^2}{I_o \varepsilon(\theta) D^2}.$$

Hence the cross section becomes

$$\sigma_L(\theta) = R(\theta) \frac{d^2r^2}{D^2N},$$

where

$$R(\theta) = \frac{I(\theta) \varepsilon(0^\circ)}{I_o \varepsilon(\theta)}.$$

The relationship between the center of mass (CM) and laboratory (LAB) cross sections is given by

$$\sigma_{CM}(\theta) = \sigma_L(\theta) \frac{\sin^2(\theta) \cos(\Theta-\theta)}{\sin^2(\Theta)}.$$
where $\theta$ is the CM angle. Cross sections listed in this chapter are in the CM system.

Use of a scattering sample of finite size introduces several effects which should be taken into account. One of these effects is the attenuation of the neutron beam in the sample. Sample nuclei located near the rear of the sample are not exposed to the same incident flux as those near the front. The correction for this attenuation can be obtained by replacing the direct flux with the average flux within the sample.

Another effect of the size of the sample is to cause some of the scattered neutrons to be scattered again before emerging from the sample. This effect is called multiple scattering. Multiple scattering usually can be neglected for samples with dimensions less than 0.2 mean free paths, and can be calculated for larger samples using Monte Carlo techniques (Wa 63 and Re 67).

Because of the nature of the detecting scintillator, the detecting efficiency changes with neutron energy and thus scattering angle. For an unbiased detector, the energy dependence of the efficiency is mainly a consequence of the energy dependence of the neutron-proton total cross section. Also, the finite size of the detecting scintillator introduces attenuation effects in the same manner as the sample. For a detector with a fixed bias it must be taken into account that the detecting system does not count the same fraction of neutrons as the neutron energy changes. In addition, multiple scattering in the detector is important. For example, neutrons which normally produce
pulses below the detector bias can be scattered again in the scintillator and produce two scintillation pulses which are summed by the detection system resulting in a pulse which is counted. All of these factors contribute to what is termed the detector efficiency. See reference Ma 72 for a comprehensive discussion of the factors which affect the efficiency of neutron scintillation detectors.

Due to the time required by the detection system for analysis of pulses, some counts can be lost. This dead time correction is insignificant for counting rates less than 2 kHz.

Some of the corrections mentioned above, for example, the variation of the detector efficiency with energy, are difficult to compute accurately. Estimates of the magnitudes of these corrections for the present work are given in Table II for a few angles. The present data were corrected only for variations in n-p total cross section and effects due to detector bias. The remaining effects in Table II were not considered in correcting the data. It is noted that the largest uncertainty is associated with the neutron detector efficiency. This uncertainty could have been reduced considerably by measuring the relative efficiency of the detector in a separate experiment, which is the usual procedure.

C. Results and Discussion

The measured differential cross section for carbon at $E_n = 7.0$ MeV is shown in Figure 14. The data are presented with that measured by Galati et al. (Ga 72) using the PBM at $E_n = 6.94$ MeV. The error
## TABLE II

**ESTIMATES OF CROSS SECTION CORRECTION FOR ELASTIC SCATTERING OF 7 MeV NEUTRONS FROM CARBON**

<table>
<thead>
<tr>
<th>Angle LAB</th>
<th>Attenuation in Sample</th>
<th>Multiple Scattering in Sample</th>
<th>Attenuation in Detector</th>
<th>Variations in $\sigma_{np}$</th>
<th>Detector Bias</th>
<th>Multiple Scattering in Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>+16%</td>
<td>-6%</td>
<td>+1%</td>
<td>-1%</td>
<td>+2%</td>
<td>-2%</td>
</tr>
<tr>
<td>90</td>
<td>+21%</td>
<td>-8%</td>
<td>+4%</td>
<td>-11%</td>
<td>+32%</td>
<td>-3%</td>
</tr>
<tr>
<td>130</td>
<td>+19%</td>
<td>-9%</td>
<td>+6%</td>
<td>-19%</td>
<td>+92%</td>
<td>-4%</td>
</tr>
</tbody>
</table>

*) Data plotted in Figure 14 were corrected for $\sigma_{np}$ variations and detector bias.
Figure 14

The $^{12}\text{C}(n,n)^{12}\text{C}$ differential cross section at a neutron energy of 7.0 MeV. The points plotted represent the measurement made in the present work, corrected for changes in $\sigma_{np}$ and bias effects only. Error bars are statistical only. The curve drawn represents a 5th order Legendre-polynomial fit to the data of Galati, et al. (Ga 72) at a neutron energy of 6.94 MeV.
bars shown for the present work represent statistical errors. The
data shown were corrected for variations in n-p total cross section
and effects due to detector bias.

In addition to the statistical error shown, each datum of the
present work has a systematic error associated with each of the cor­
rections mentioned in Section III B. The uncertainty arising from
the background correction and from the normalization procedure are
believed to be about 3% and 2%, respectively. The uncertainty as­
sociated with the factors listed in Table II for which no corrections
were made ranges from +9% at 30° to +12% at 130°.

The neutron energy spreads caused by the finite polyethylene
target thickness and the angular width of the carbon sample were 180
keV and 170 keV, respectively, resulting in a total neutron energy
spread of about 250 keV. In view of the differences in neutron en­
ergy and neutron energy spread, perfect agreement between this data
and that of Galati is not expected. However, the agreement between
the data of the present work and that of Galati et al. is good. Good
agreement is expected since the total cross section does not seem to
be changing drastically with neutron energy (Fo 61).
IV. CONCLUSIONS

It has been demonstrated that the APM can be used to measure differential cross sections for the elastic scattering of 7 MeV neutrons. During the course of this work, however, it has been found that at present the technique has several limitations. The most serious limitation is the small neutron flux. For example, it does not appear to be feasible to accurately measure differential cross sections for inelastically scattered neutrons because of this small flux. Another limitation is the presence of a relatively large background from the source reaction, in spite of the associated particle coincidence requirement. Possible solutions to these problems are discussed below.

In principle, the neutron flux can be increased by using D(d,n) neutrons emitted at more forward angles. However, although the neutron flux is increased, there are several complications produced by this solution. One complication is that polarization of the neutron beam necessitates measurement of the scattered neutron flux on both sides of zero degrees. This measurement is difficult at forward angles primarily due to the presence of the beam dump. Another complication is that these forward angles have small associated particle energies, making separation of the reaction products difficult. Lastly, background from deuteron break-up, for which the cross section increases with decreasing angle, will cause higher accidental count values.
A second approach to increasing the neutron flux would be to change the source target. An adequate increase in the neutron flux could not be obtained by producing thicker targets since targets thicker than 30 μm make separation of the $^3$He particles and deuterons very difficult. By combining 20 - 30 μm targets with larger incident beam currents, however, an acceptable increase in the neutron flux could be produced. The beam heating effects could be minimized by high speed rotation of the target rather than wobbling it. For example, Hagengruber (Ha 71) was able to use beam currents of 750 na with little target deterioration by rotating a deuterated polyethylene foil at 200 rpm. Also, it is possible that the target deterioration that results from larger beam currents can be reduced by coating the incident side of the target with a thermally conductive material such as aluminum.

The background caused by neutrons from the source reaction which do not scatter from the sample could be reduced substantially by employing large masses of shielding material such as used in the PBM, rather than shadow shielding. Unfortunately, the expense of such extensive shielding would negate one of the advantages of the APM.

A comparison of the APM with the PBM is quite useful. Table III compares some of the parameters used in the present experiment and a similar one using the PBM. Since the PBM uses the neutrons produced at zero degrees by the D(d,n)$^3$He reaction, the available neutron flux is much larger. At an incident deuteron energy of 10 MeV, for example, the reaction cross section at zero degrees is 10 times larger than at...
TABLE III

A COMPARISON OF THE EXPERIMENTAL PARAMETERS FOR THE APM AND THE PBM
FOR THE MEASUREMENT OF THE $^{12}$C(n,n)$^{12}$C DIFFERENTIAL CROSS SECTION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>APM (present work)</th>
<th>PBM (Galati, et al.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Producing Reaction</td>
<td>D(d,n)$^3$He at a lab angle of $66.5^\circ$ to produce unpolarized 7.0 MeV neutrons</td>
<td>D(d,n)$^3$He at a lab angle of $0^\circ$ to produce unpolarized 6.94 MeV neutrons</td>
</tr>
<tr>
<td>Incident Deuteron Energy</td>
<td>9.5 MeV</td>
<td>3.7 MeV</td>
</tr>
<tr>
<td>Source Target</td>
<td>Self-sustaining foil of deuterated polyethylene 25 µm thick</td>
<td>Deuterium gas cell 0.9 cm dia. x 3 cm long operated at 1 atm. pressure</td>
</tr>
<tr>
<td>Incident Beam Current</td>
<td>0.15 µamp direct current</td>
<td>2 µamp, average, pulsed and bunched into 1 nsec bursts</td>
</tr>
<tr>
<td>Neutron Energy Spreads</td>
<td>175 keV due to source target thickness; 80 keV/degree at sample</td>
<td>20 keV due to source target thickness; 13 keV/degree at sample</td>
</tr>
<tr>
<td>Neutron Flux</td>
<td>$5.7 \times 10^4$ neutrons/str.-sec</td>
<td>$1.3 \times 10^8$ neutrons/str.-sec</td>
</tr>
</tbody>
</table>
an angle of 60 degrees. Also, the use of gas targets by the PBM allows much larger incident beam currents to be used than used in the present work with wobbled foil targets. Since a much larger incident neutron flux is available, smaller scattering samples and larger sample to detector distances can be used with the PBM to improve energy and angular resolution. These factors, then, combine to make the PBM somewhat superior to the APM.

The APM and the PBM have similar timing resolutions. The resolution of the present work was typically 2.1 nsec, while the resolution reported by Galati (Ga 72) using the PBM was approximately 2.0 nsec. Galati also reports a foreground to background ratio of 4:1 using extensive shielding composed of lithium carbonate doped paraffin and lead with the detector approximately 1.8 m from the source reaction. The same ratio for the present work was typically 3:1 using crude shadow shielding with the detector at a distance of only 0.8 meters. It should be pointed out that unlike the case for the PBM, the background of the APM is not time dependent. Thus, in many cases it may be possible with the APM to take background and foreground data simultaneously, as was done in the present work.

At the present time, it appears that the APM may not be able to compete with the PBM on even terms for measuring neutron differential cross sections, primarily because of the lower neutron flux. The main advantage of the APM, at its present stage of development, appears to be its application to measuring neutron differential cross sections at accelerator installations which do not have the capability of pulsed beam operation.
An important application of the APM lies in the capability to produce a known flux of neutrons. This capability makes possible measurements of absolute cross sections in the MeV range. Also, it is possible that the background reducing feature of the technique could be applied to neutron capture experiments. Since large NaI crystals are very efficient, the relatively low neutron flux could be tolerated even though the cross sections for such reactions are very low for MeV neutrons. The technique can also be used to measure neutron induced particle reaction cross sections using the detecting scintillator as the target. For example, Bartle (Ba 73) has studied the $^{40}\text{Ca}(n,n')$ reaction by bombarding a CaF$_2$ scintillator with neutrons from the D(d,n) reaction. However, the number of reactions which can be studied this way is severely limited, since only a few substances can be used effectively as scintillators.
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