The Differential Elastic Scattering of 3.15 Mev Neutrons by Aluminum, Sulphur, Vanadium and Cobalt.

Roy Anthony Lambert

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A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Physics

by

Roy Anthony Lambert
B.S., Loyola University, 1957
M.S., Louisiana State University, 1961
May, 1966
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ABSTRACT

The differential elastic cross sections of Al, S, V and Co for 3.15 Mev neutrons have been measured by the time of flight technique. The particular version of this method was velocity determination of the scattered neutrons by pulsed beam utilizing a Van de Graaff generator to produce neutrons by means of the D(d,n)He reaction. Beam pulsing is accomplished with a Mobley variable path magnetic ion buncher. The spread in energy of the neutron beam was ±0.15 Mev and burst duration was 2.5 nanoseconds.

Measurements were made at 10° intervals from 20 to 140 degrees over a 125 cm. flight path. Scattering material is in the form of right circular cylinders 5/8" X 2". The detector is a stilbene crystal mounted on a 56AVP photomultiplier mounted in a shield containing paraffin and lithium carbonate for neutron attenuation as well as lead to stop gamma photons. Photomultiplier pulses are processed in a time to pulse height converter which feeds them to a TMC 400 channel analyzer. Energy resolution was 14.5%.

The raw data was converted into absolute cross sections by normalizing to the direct beam count at 0°. The angular distributions so obtained are compared to published values at nearby energies and to the general predictions of optical model theory. A check of the 0° cross section was also made by means of Wick's limit. The results are seen to be generally in good agreement with expected values.
CHAPTER I

INTRODUCTION

Over the last several decades the study of nuclear structure has progressed from the experiments of Rutherford demonstrating the existence of the atomic nucleus to the present-day developments in which particles ranging from gamma photons to light nuclei bombard targets with energies of the order of billions of electron volts. Fission reactions also contribute to our understanding of the nucleus, however they give essentially only the grossest characteristics such as particle separation energy and nuclear binding energy. It is primarily through experiments involving a well-defined beam of particles incident on a particular target that a more detailed knowledge of the nature of nuclear forces is evolving, including, e.g., their dependence on charge, spin, parity, symmetry properties, mesic nature and momentum. In general it is hoped that studies of this type will lead to a better idea of the entire physics of the nucleus.

The latter class of reactions mentioned above can be subdivided further into two main categories, viz., elastic and non-elastic (including inelastic) reactions. Elastic scattering is defined as that in which the kinetic energy of the colliding particles remains constant in the center-of-mass system. Any other type, whether it be a direct reaction process, including collective excitation and stripping for example, or an absorption process such as inelastic scattering is called a non-elastic collision. Elastic scattering may be further
broken down into shape elastic or potential scattering in which the interaction is essentially that of a single particle with a potential well and compound elastic scattering in which the incident particle is absorbed forming a compound nucleus with the target nucleus which then reemits the incident particle with the same energy as that in potential scattering. It is not possible to distinguish between the two cases experimentally.

Although in principle elastic scattering represents one of the simplest types of interactions it nevertheless is advantageous to study from a theoretical viewpoint. The method of attack usually proceeds from the adoption of a particular model of the nucleus to an associated scheme for the reaction which can then be checked with experiment. At low energies the interaction may be looked at according to the shell model of the nucleus in which the incident particle may be considered to be in the average field of all the nucleons and experiment will thus afford information about the statistical properties of the target nucleus. High energy experiments yield data about inter-nucleon forces and their accompanying complexities. The former is essentially a two-body problem while the latter is a many-body problem which cannot be analyzed without a number of simplifying assumptions. The simpler case of elastic scattering gives the theorist an opportunity to test the validity of a particular model and collision theory which can then be applied to more complex situations.

The two-body problem in itself can give directly meaningful results if looked at according to the optical model of the nucleus; for example, in the case of polarization experiments, a special class of elastic scattering experiments. In direct analogy with polarization
by successive scatterings in classical wave optics a beam of particles is made to undergo consecutive collisions which, because of the spin-orbit interaction of the particle, allows the investigator to select particles of a particular spin state or polarization which can then be used to furnish more detailed information about the spin-orbit part of the potential. This wave-mechanical picture may be carried a step further by looking at the angular distribution of elastically scattered particles. The resultant curve is that of a diffraction pattern with its customary strong maximum in the forward direction and successive maxima and minima. The application of optical model theory to these experiments and others over a wide range of energies has yielded gratifying results warranting further discussion of this model.

The optical model was first developed semi-classically by Fernbach, Serber and Taylor\(^1\) in 1949 in order to explain some of the results of high energy neutron experiments which were at variance with the predictions of the older compound nucleus theory of Bohr.\(^2\) In particular, the compound nucleus scheme assumed complete absorption of the incident particle by the bombarded nucleus to form a composite system which subsequently decayed by means of various channels depending upon the particular nucleus but independent of the formation of the compound nucleus. This theory successfully predicted the variations of the total cross section with energy for low energy neutrons.


including the many sharp resonances exhibited in the data. For high
energy experiments however, the strong absorption attendant with this
idea was much greater than that borne out by experiment. The optical
model not only gave satisfactory results when applied to these cases,
but also to low energy cross sections as a function of energy when the
latter were averaged over many resonances, a place where the shell
model had failed.

The optical model may be exemplified by a complex potential:

\[ V = U + iW \quad r < R_c \]
\[ V = 0 \quad r > R_c \]

where \( U \) is related to the shell model potential, \( W \) takes into account
the absorption and \( R_c \) is the distance beyond which the nuclear poten-
tial is negligible. The result forms a compromise between the shell
and compound nucleus models. When this form of the potential was
applied quantum-mechanically by Feshbach, Porter and Weisskopf in
1954 to the data of Barschall and others for total cross sections

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5. D. W. Miller, R. K. Adair, C. K. Bockelman and S. E. Darden,
"Total Cross Sections of Heavy Nuclei for Fast Neutrons", Physical
Review, LXXXVIII (1952), 83.

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vs. energy the agreement was highly satisfactory considering the fact that the shape of the potential used was one of the crudest, namely, a square well. Further, the differential cross sections also showed the diffraction pattern portrayed by the data. Subsequently the theory has been applied to experimental results in the energy range of 2-300 Mev. including protons, alpha-particles and heavier nuclei as bombarding particles as well as to pion and muon scattering with significantly good results, thus adding plausibility to the concept of the nucleus as a "cloudy crystal ball" with an index of refraction.

The optical model theory has thus been an amalgam for the wave mechanical notions of polarization by reflection and diffraction phenomena with the shell and compound nucleus theories. It does not however, solve all the problems of nuclear structure and indeed gives only a relatively gross idea of it, yet it is a powerful tool when utilized to understand the results of elastic scattering experiments which, as mentioned earlier, can give the form of the spin-orbit as well as the central part of the potential. Another pertinent feature of this model is the fact that it can be applied to already existing elastic scattering data to interpolate for the cross sections of


materials not measured experimentally by means of a method due to Beyster\textsuperscript{12}.

With the development of such strong theoretical support for the gathering of differential elastic scattering data there follows the need for an experimental method which will yield the type of data compatible with the elegant mathematical structure associated with it. First, the type of particle must be selected. The neutron, because of its electrically neutral nature and hence lack of interaction with the Coulomb field of the nucleus is a likely particle to test the inherent character of the specifically nuclear forces. At the same time, however, this lack of charge presents experimental difficulties. In cases where an accelerator is used to provide neutrons they must be produced by charged particle interactions. If detection is by means of a scintillator-photomultiplier arrangement neutron energy must be converted indirectly into an electrical signal by producing accelerated charged particles. The former condition has been satisfied in the present case by using the D(d,n)He\textsuperscript{3} reaction, the latter by using a hydrogenous crystal, stilbene, and utilizing the large (n,p) cross section to produce energetic recoil protons which are then easily detected by the scintillations produced in the crystal. A third condition imposed in a neutron scattering experiment if meaningful data is to be obtained is the separation of the elastically scattered neutrons from the inelastic. At present one of the popular and powerful means of achieving this is the method of time-of-flight.

The time-of-flight technique makes use of the fact that neutrons of different energy have different flight times over a given path and hence greater and lesser velocities. The time taken to traverse this path can be determined and the varying time intervals serve as a measure of neutron energy. More importantly, time can be converted to an easily measured electrical quantity such as voltage and discrimination between differing pulse heights corresponding to different flight times and energies separates the neutrons of interest from others, if the resolution is adequate. The discrimination is accomplished by a pulse-height analyzer which, after sorting the separate pulses according to height stores the count of each in a scaling device. The output of these scalers, when plotted against pulse height or scaling number, will then give the distribution of particles in the elastic and inelastic categories. Gamma photons associated with inelastic collisions will also be separated from the neutrons because of their greater velocity. This method permits a considerable reduction in background prevalent with other methods of detection.

There are two main variations of the time-of-flight method. One is the associated particle method in which a charged particle emitted in the neutron-producing reaction is detected thus fixing one end of the time interval to be measured while the other end point is provided by the arrival of the neutron at the detector. The other technique is that called velocity determination by pulsed beam. In this method the neutrons are produced in bursts of very short duration while the electronic signal associated with each burst and in fixed phase relationship to it is used to fix the starting point of the time interval while the pulse produced by the scattered neutron at the
detector serves to fix the length of the interval. For elastic scattering it is not necessary in either method to perform an energy calibration of the analyzer for the scattered neutrons since their energy is known from the mechanics of the neutron-producing reaction and only their separation from the inelastically scattered neutrons is important. This separation will depend on the time width of the neutron pulse and the overall resolution of the detection system or instrumental resolving time. When well separated the total number of elastically scattered neutrons at a given angle can then be used to determine the differential cross section at that angle.

The specific aim of the experiment described herein is to measure the angular distribution of neutrons elastically scattered from elements covering a limited range of atomic mass numbers, in particular, Aluminum, Sulfur, Vanadium, and Cobalt with A equaling 27, 32, 51, and 59, respectively. The choice of scatterers was dictated by considering the high relative natural abundance of each isotope thus eliminating the need for taking into account the scattering from other isotopes or elements in the laboratory form of each. For Cobalt and Vanadium there is little published angular distribution data at energies below 7 Mev and it is hoped that this experiment will serve to help fill that void.

Another aspect to be explored is the variation of the differential cross section with mass number according to optical model predictions. This model predicts diffraction patterns with successively stronger principal maxima and deeper first minima as well as an increasing number of secondary maxima and minima as mass number and energy are increased. At the lower end of the fast neutron spectrum
of energies (1 Mev) the above predictions are borne out only as A be-
comes very large (A > 150). For neutrons of 3.15 Mev energy, the
value to be used in this experiment, the effect should become more no-
ticeable at smaller values of A as indeed will be seen to be the case.
The data so obtained is to be compared with other published data at
energies proximate to that utilized here and to the general predictions
of optical model theory.
CHAPTER II

APPARATUS AND PROCEDURE

Apparatus

The apparatus in use at L.S.U. for the measurement of angular distributions of elastically scattered neutrons is a fast neutron spectrometer employing a Van de Graaff accelerator, Mobley Ion Buncher\(^1\) and associated time-of-flight equipment. The particular time-of-flight technique is the pulsed beam method with a time signal derived from the R-F voltage used to produce bursts of ions and subsequently neutrons.

A. Production of neutrons

1. Ion source

An R-F ion source of the type developed by Moak, Reese and Good\(^2\) at Oak Ridge is incorporated in the accelerator and provides the deuterons used in the D(d,n)He\(^3\) reaction. After extraction from the source the ions are accelerated by the Van de Graaff and then magnetically analyzed to separate the deuterons from any other ions.

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formed in the gas discharge. After selection of the proper beam component the continuous beam is steered into the R-F chopping section of the Ion Buncher.

2. Ion Buncher (Fig. 1)

The continuous beam from the Van de Graaff is chopped into bursts of approximately 40 nanosecond duration by deflection through three sets of dual plates across each of which is an R-F voltage (4500 v. peak to peak). The phase of the sweep voltage is the same at each set of plates while the spacing and their length is dictated by a quantity $\lambda^3$ called the ion wave length.

$$\lambda = \frac{v}{f}$$

where $v$ is the ion velocity and $f$ the sweep frequency. This spacing is one-half $\lambda$ and the phase change is $180^\circ$ thus allowing only ions entering the chopping region at the right phase of the sweep voltage to pass. A chopping block inserted part-way into the path of the ions traveling along the line through the mid-point of the space between the plates selectively removes one of the two possible components of the beam which would otherwise pass for each half-cycle of R-F sweep.

After traversing this section the individual bursts are swept across the input face of the bunching magnet by another set of plates spaced one-fourth $\lambda$ before the last set of chopping plates. The effect of these plates is to deflect successive portions of a given ion burst in a direction such that the lead ions in a burst travel a longer flight path through the magnet than those arriving later in a

---

FIG. 1
ION BUNCHER
manner such that all arrive at a fixed point beyond the magnet at the same time, being brought to a focus by the magnet itself. Final focusing on the target is accomplished by three sets of electrostatic lenses which, with the aid of two collimators, produce a beam spot size of three-eighths inch.

3. Gas Target

The target cell containing deuterium gas is made in two parts (Fig. 2). The front piece is made of copper with a hexagonally close packed grid of holes of .046 in. diameter spaced .015 in. apart to allow maximum beam passage while supporting a nickel foil. The foil is 25 microinches thick to reduce as much as possible the energy loss of the incident beam. It is bonded at its periphery to the grid by a solution of vinyl plastic in acetone forming a gas-tight seal. Because of heat dissipation of the energy of the incident deuteron beam cooling must be provided and this is done by means of an air conduit around the outer diameter of the grid. Gas pressures were nominally 15.0 psi.. absolute ±0.5 psi.

B. Scatterers

The Al, S, V, and Co scatterers were in the form of right circular cylinders 5/8 in. in diameter and 2 in. long. The Al, V and Co cylinders were easy to prepare because of their malleability; however, the S presented considerable difficulty in preparation because of its brittleness in the prepared form. After a number of unsuccessful attempts it was finally turned to the proper size on a lathe. The scatterer holder was made of aluminum 1/32 in. thick supported by a steel rod 1/16 in. in diameter.
FIG. 2 — GAS TARGET ASSEMBLY

FIG. 3 — DETECTOR AND SHIELD
C. Detection of neutrons

1. Scintillator and photomultiplier (Fig. 3)

The scintillator used was a stilbene crystal 1 1/2 in. in diameter and 2 in. long. This was optically coupled to a 56AVP high gain photomultiplier operating nominally at 2200 volts. Two outputs from this tube were utilized in a coincidence counting arrangement. A fast pulse channel was used to indicate an event, a detected neutron, while the slow pulse, after shaping to meet the requirements of the pulse height analyzer coincidence input, gated the analyzer for proper coincidence. The tube was cooled by means of a copper jacket containing cooling coils through which water flowed at near freezing temperatures. This provided a stable, reproducible environment as well as reducing photomultiplier noise. Magnetic shielding was provided by a mu-metal shield.

2. Shielding (Fig. 3)

The scintillator and photomultiplier are housed in a massive shield containing lead to attenuate gamma rays and a mixture of paraffin and lithium carbonate (Li$_2$CO$_3$) to attenuate room scattered as well as background neutrons in general. This latter is accomplished by the moderation of the undesired neutrons to thermal energies, capture of these by Li to produce alpha particles which are then easily absorbed by the remainder of shielding material. The lead is in the form of rings situated concentrically along the central axis of the truncated cone forming the shield covering approximately two-thirds of its length measured from the rear of the shield. Immediately in front of the lead is a collimator filled with the paraffin - Li$_2$CO$_3$ mixture and
containing a rectangular throat through which the neutrons to be counted pass on their way to the detector. The crystal-photomultiplier combination enters the shield through a side port with the crystal in the path of the scattered neutron beam. Surrounding the lead rings and collimator is the remainder of the paraffin and Li$_2$CO$_3$. In order to shield the throat of the collimator from any neutrons coming directly from the target a shadow bar made of tungsten and iron is situated exterior to the shield and directly in front of the collimator.

3. Fast channel (Figs. 4 and 5)

a) **Tunnel diode discriminator (Fig. 4) and amplifiers.**—The fast pulse output from the photomultiplier is fed to the input of a tunnel diode discriminator whose bias is set to achieve the maximum possible signal to noise ratio. The output of this discriminator is coupled to the first of two cascaded Hewlett-Packard 460 amplifiers. This signal is then fed to one channel of the time-to-pulse height converter in order to fix one end of $t_n$, the neutron's time of flight.

b) **Time-to-pulse height converter and amplifiers.**—The TPH converter is of the type developed by Neiler$^4$ at Oak Ridge. The other input needed to fix the time interval and hence pulse height of the output signal is provided by a signal derived from the RF sweep voltage by means of a pick-up loop placed in close proximity to the tank circuit of one of the sets of deflecting plates. After being fed through a step variable delay line, the RF signal is amplified to saturation by three cascaded H-P460 amplifiers and clipped forming

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FIG. 4 — TUNNEL DIODE DISCRIMINATOR

FIG. 5 — TIME OF FLIGHT ELECTRONICS
"pips" of short duration, finally becoming the other input to the TPH converter. Although many descriptions in the literature label the RF derived signal as the start pulse and the detector signal as the stop pulse, in many applications, including the present one, the function of each is reversed. The reason for this is consideration of the tolerance to high count rates of the TMC analyzer which is 50,000 pps. as compared to the 6.8 megacycles per second of the R-F sweep voltage. Since relative separation of the elastic and inelastic peaks is of primary concern this modification presents no added difficulties. The output of the TPH converter is passed through a 3.5 microsecond delay line to ensure proper gating by the pulse from the slow channel and goes finally to the signal input of the pulse height analyzer.

4. Slow channel (Fig. 5) and preamplifier

a) Preamplifier.--A White cathode follower is used as a preamplifier and is physically situated as close to the photomultiplier as possible which in this case was at the entrance to the detector port in the shield.

b) Non-overload amplifier and pulse shaper.--The slow pulse from the photomultiplier goes to a Hamner non-overload amplifier. This amplifier is equipped with a discriminator whose output is impressed across a Zener diode. The characteristics of this diode are such that a 4 volt one microsecond pulse of 0.25 microsecond rise time, as required by the PH analyzer, is fed to the coincidence gating input of the PH analyzer. Discriminator bias for the Hamner amplifier was set by observing a Co$^{60}$ reference pulse-height spectrum and adjusting the discriminator helipot for a low noise level affording the
optimum signal-to-noise ratio under the operating conditions.

5. Pulse height analyzer and printer

The pulse height analyzer used to obtain spectra is a Technical Measurements Corporation (TMC) Model 402 dual input 400 channel instrument with coincidence-anti-coincidence modes of operation and CRT display. The baseline and gain settings of this device were such as to allow positioning of the entire range of TPH pulses within a 100 channel segment of the analyzer's memory with the elastic and inelastic neutron peaks as well as the gamma peaks suitably spaced to afford the most information. Although the entire memory was available for storage on any run only one quadrant was used so as to provide an instantaneous comparison of scattered and background spectra. Further, it was found that using only one quarter of the memory at a time still allowed for a reasonable number of channels for statistical purposes as well as time calibration. Live time data for a particular run were stored in the magnetic core memory of the TMC and printed on a TMC printer at the conclusion of a run.

6. Monitor (Fig. 6)

Although the scattered neutrons of interest are detected by the crystal and photomultiplier in the shield mentioned earlier a second detector is placed in a smaller shield at 90° with respect to the incident beam and above the target to receive an unscattered flux of neutrons. This monitor count serves as a normalization factor for each angular setting by providing a fixed number of total counts to be reached independent of fluctuations in deuteron beam current on target. For this purpose a second 56AVP with plastic scintillator is
FIG. 6 - NEUTRON MONITOR
used, the output of which is again fed to a White cathode follower before amplification by a Hamner Non-Overload Amplifier. This amplified output is then fed to a suitably biased scaler to obtain the desired normalization total count.

Procedure

In preparing to take data for an angular distribution the Van de Graaff, Ion Source, Ion Buncher and detection system were run for one to two hours in order to assure beam stability and equilibrium conditions. In addition the water-cooling system was operated for the same period of time so that thermal equilibrium would be reached. The choice of method for measuring absolute differential cross sections dictated taking data with the detector at $0^\circ$ with respect to the incident beam of neutrons without the scatterer in place and thus after this initial warm-up period the shield was moved to the forward direction and several runs were made to afford a good average value for the direct beam count. The detector was returned to the forward direction after every two or three angular settings in order to take into account any drift in the electronics between direct beam measurements. For these direct beam counts the beam current was reduced from the average of 6 to 8 microamperes of deuterons incident on target during runs at the various angles to 3 to 4 microamperes in order not to overload the TPH converter.

The range of angles measured was from 20 to 140 degrees. At angles smaller than 20 degrees the number of neutrons reaching the detector directly from the target was too great to allow sufficient shielding with the shadow bar. The limit in the back direction is
imposed by the bulk of the shield which came in close proximity to the drift tube of the accelerator at 140 degrees. At a given angular setting scattered count records were made with the scatterer out to provide a background count and then with each of the several scatterers in place. Each separate run lasted from 10 to 20 minutes until a total of 192,000 counts were accumulated in the monitor scaler. The stored count in the analyzer for each run was then printed out for later analysis.

Ion burst duration was measured with a Tektronix 545 Oscilloscope equipped with a Type N plug-in unit. The signal from a probe inside the drift tube of the accelerator was fed to a Type 110 Pulse Generator and Trigger Take-Off System which provided the proper triggering of the 545 for a display of the ion burst width. Measurements made in this way showed a nominal 2.5 nanosecond pulse width.

Time calibration of the PH analyzer was accomplished by varying the position of the elastic peak in the spectrum with the step delay line in the stop channel of the TPH converter. This delay is changed a fixed number of nanoseconds during repeated runs at a given angle (0°) and an average is taken of the number of channels through which the peak shifts for each of the increments in delay. The time per channel is obtained by dividing the delay in nanoseconds by the number of channels between peaks. In this case this figure was 1.25 nanoseconds. Since the experimental peaks are approximately 5 channels wide (full width-half maximum) the time resolution is 6.25 nanoseconds. Representative spectra are shown in figures 7 through 11.
FIG. 7
DIRECT BEAM TIME SPECTRUM (0°)

CHANNEL NUMBER

COUNTS PER CHANNEL

20000
17500
15000
12500
10000
7500
5000
2500

NEUTRONS

GAMMA PEAK
**FIG. 8** $^{32}$S CORRECTED TIME SPECTRUM
$	heta_1 = 40^\circ$

**FIG. 9** $^{32}$S UNCORRECTED TIME SPECTRUM
$	heta_1 = 40^\circ$

- SCATTERER IN
- SCATTERER OUT

1 CHANNEL = 1.25 nsec.
FIG. 10 $^{60}$Co CORRECTED TIME SPECTRUM
$\theta_i = 40^\circ$

FIG. 11 $^{60}$Co UNCORRECTED TIME SPECTRUM
$\theta_i = 40^\circ$
- SCATTERER IN
- SCATTERER OUT
| CHANNEL = 1.25 nsec.

GAMMAS

INELASTICALLY SCATTERED NEUTRONS
CHAPTER III

ANALYSIS OF AND CORRECTIONS TO DATA

Analysis

Before utilizing the raw data obtained from the analyzer certain other factors have to be known to convert this data into cross sections because of the non-ideal experimental conditions, such as a relatively thick target and extended form of the scatterer. The number and energy of neutrons produced in the $D(d,n)He^3$ reaction are sensitive both to the energy of the deuterons and the angle at which they are measured. Since the target is thick and charged particles give up their energy readily in traveling through matter neutrons of different energies are produced at different points in the target because of the straggling in energy of the deuterons traversing the target. Thus the energy of the deuterons at a number of representative points in the target will have to be determined and with this the cross section for the neutron producing reaction can be obtained from published tables.\footnote{J. B. Marion, Nuclear Data Tables, Part 3, (Washington: U.S. Government Printing Office, 1960).} The neutron energy associated with deuterons of a particular energy can similarly be found. The overall effect in producing neutrons can then be obtained by summing the contributions from each of the various points in the target. Likewise, the average neutron energy and the effective spread in energy can be calculated.
The determination of deuteron energy at different points proceeds from a consideration of the following relation:

\[ \xi = -(1/N)(dE/dX) \]  

where \( \xi \) is the stopping cross section of the atoms or molecules of the medium under consideration expressed in ev-cm.\(^2\):

\[ N = \text{number of atoms or molecules per cm.}^3 \]

\( dE/dX \) = energy loss per unit path length

If the latter were a linear function of distance through the absorbing medium the energy loss and hence remaining energy at each point in the target could be quickly determined. Unfortunately, no such simple relation exists. In fact, the stopping cross section in a given material is a function of the velocity as well as the charge of the incident particle.\(^2\) Thus it is necessary to make a simplifying assumption, namely, that over a small distance \( \Delta X_i \) in the target the energy loss is given by:

\[ E_i = -\xi_i N \Delta X_i \] (2)

where \( \xi_i \) is determined graphically for the incident deuteron energy at each segment of the target. A starting value is obtained by calculating the energy lost in traversing the nickle foil using the same approximation as above. Using the appropriate graph and conversion factors\(^3\) the energy lost in the foil is found to be 140 kev. which leaves the deuterons incident on the first gas segment with an energy of 360 kev. Repeating these calculations for each of the \( i \) segments


\(^3\)Ibid., 201.
the energy loss in each of these and consequently the incident energy at each subsequent segment is determined. With this calculated data a table can be formed listing deuteron energy and the associated D(d,n) cross section with its accompanying neutron energy (Table I). The cross sections will be useful for later calculations while the neutron energies can be used to calculate the effective energy spread and average energy of the neutrons produced.

Since the neutron energy is a function of deuteron energy and angle of neutron direction the averaging will be done using the neutron producing reaction cross section as the weighting function. With this, \( \bar{E}_n \), the average neutron energy is given by:

\[
\bar{E}_n = \frac{\sum \sigma(E_{d_i})E_{n_i} \Delta E_i}{\sum \sigma(E_{d_i}) \Delta E_i}
\]

where \( \Delta E_i \) is given by \( (dE/dX) \Delta X_i \) and \( \sigma(E_{d_i}) \) is the D(d,n) cross section for deuterons of energy \( E_{d_i} \). The summation is over the number of segments in the target which in this case is equal to eleven and each \( \Delta X_i \) is 0.1 cm.

Having determined \( \bar{E}_n \), the effective spread in neutron energy can be computed from the following:

\[
\Delta \bar{E}_n = \frac{1}{k} \sum_{i=1}^{k} |\bar{E}_n - E_{n_i}|
\]

Using \( \bar{E}_n \) from above and \( E_{n_i} \) from the table the spread is seen to be \( \pm 0.150 \) Mev.

In the foregoing analysis only the 0° neutrons were considered. Although in the following the angular spread of neutrons will be discussed it is only the relative number of neutrons in small angles about
<table>
<thead>
<tr>
<th>Segment (i)</th>
<th>$\Delta X_i$ (cm.)</th>
<th>$E_{D_i}$ (Mev)</th>
<th>$d\sigma/d\Omega(0^\circ,E_{D_i})$ (mb/ster.)</th>
<th>$(dE/dX)_i$ (MeV/cm.)</th>
<th>$E_{n_i}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>0.360</td>
<td>12.50</td>
<td>0.210</td>
<td>3.30</td>
</tr>
<tr>
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<td>0.1</td>
<td>0.339</td>
<td>11.95</td>
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<td>3.27</td>
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<tr>
<td>3</td>
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<td>0.233</td>
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<td>11</td>
<td>0.1</td>
<td>0.084</td>
<td>1.60</td>
<td>0.380</td>
<td>2.79</td>
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</table>
$0^\circ$ as determined by the $D(d,n)$ cross section which are of importance in determining flux. Since their loss in energy is small compared to the forward direction neutrons this effect was neglected in the above.

Having determined the $D(d,n)$ cross section at various points in the target the analysis can now be extended to the scattering of the neutrons produced at these points by the scatterer. It is more convenient to start from an expression for the scattered yield than the defining equation for cross sections as will be seen in the following. This expression is given by:

$$N_n(\text{scattered}) = I_n(\text{incident})d\sigma/d\Omega(E_n,\Theta)N_s \Delta t_s A_s$$

(5)

where $N_n(\text{scattered})$ = number of neutrons of energy $E_n$ scattered into unit solid angle about $\Theta$/sec.

$I_n(\text{incident})$ = neutron flux (neutrons/sq.cm./sec.) incident on scatterer

$d\sigma/d\Omega(E_n,\Theta)$ = differential cross section for scattering of neutrons of energy $E_n$ into unit solid angle about $\Theta$ in laboratory system of coordinates; defined as (number of neutrons of energy $E_n$/steradian/sec.) $\times$ (number of incident neutrons/sq.cm./sec.)

$N_s$ = number of scattering nuclei per unit volume of scatterer

$\Delta t_s$ = thickness of scattering material

$A_s$ = area of scattering sample normal to incident beam
The factor \( \frac{d\sigma}{d\Omega} \) is that to be calculated and is derived theoretically under the assumptions of a thin scatterer and an incident parallel monochromatic beam. Satisfying these conditions experimentally requires "good geometry" which is not always obtainable in practice. Because of the thickness of the scatterer, its length and the fact that neutrons are emitted at all angles from different points in the target thus forming a divergent beam, the above expression for the scattered neutrons has to be modified and considered as pertaining to a small representative volume element of area \( \Delta A_s \) in the scatterer. The net contribution to the scattering can then be obtained by summing over the target and the scatterer.

The attenuation of the incident neutron beam due to scatterer thickness is taken into account by multiplying (5) by \( \exp(-N_s \sigma_t t_s) \) where \( \sigma_t \) is the total cross section for 3.15 Mev. neutrons. Another aspect associated with the problem of thickness is that of multiple scattering however, since the mean free path in each scatterer is large compared with the diameter it will not be treated in the present instance.

The divergence of the neutron beam and the length of the scatterer contribute to the yield at a particular \( \Theta_i \) by adding neutrons scattered at angles other than the desired \( \Theta_i \) but which nevertheless are able to reach the detector. Since the incident intensity at each scattering element varies as the angle between the radius vector from the target point to the element under consideration and the direction of the incident deuteron beam each of these angles must be determined. This is done by analyzing the experimental geometry in terms of its known distances and consulting a table for the D(d,n) reaction as a
function of angle (Table II). The expression for the flux incident on the representative element from a particular target point where the deuteron energy is $E_d$ is given by:

$$I_n(\text{incident}) = I_d(\text{incident})d \sigma/d\Omega [\delta(D,d),E_d] N_t \Delta t_t A_t$$

(6) times $(d\Omega_{ts}/\Delta A_s)$

where $I_d(\text{incident}) = \text{incident intensity of deuterons on target}$

$d\sigma/d\Omega [\delta(D,d),E_d] = \text{neutron producing reaction cross section in lab system for deuterons of energy } E_d$

$N_t = \text{number of target nuclei per cm.}^3$

$\Delta t_t = \text{thickness of target segment under consideration}$

$A_t = \text{area of target segment}$

$d\Omega_{ts} = \text{solid angle subtended by scatterer element at point in target}$

$\Delta A_s = \text{area of scatterer element}$

The quotient in (6) converts the scattered flux from neutrons per solid angle to intensity - neutrons/sq.cm./sec.

In addition to the above the detected yield will also include the detector efficiency $\eta(E_n)$ and the element of solid angle $d\Omega_{sd}$ subtended by the detector at the scatterer element. Combining all these gives the following:

$$N_{sc}(\text{det.}) = \sum_t \sum_s \eta \exp(-N_s \sigma_{ts}) I_d(\text{inc.})(d\sigma/d\Omega)_{D,d} N_t \Delta t_t$$

(7) times $A_t (d\Omega_{ts}/\Delta A_s) \sigma/d\Omega (E_n, \Theta_i) N_s \Delta t_t A_s d\Omega_{sd}$

If the above relation is to be used to calculate $d\sigma/d\Omega (E_n, \Theta_i)$ it must first be put in a form more suitable for ready computation.
TABLE II

D(d,n)He$^3$ CROSS SECTION (MILLIBARNS PER STERADIAN)

<table>
<thead>
<tr>
<th>$\Theta$ (deg.)</th>
<th>$E_{D_1}$ (Mev) = 0.156</th>
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<th>0.270</th>
<th>0.362</th>
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<td>3.33</td>
<td>4.54</td>
<td>6.34</td>
<td>07.64</td>
</tr>
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</table>
Since $d\sigma/d\Omega(E_n, \Theta_i)$ is different for each of the angles involved in the scattering an average must be taken denoted by $\overline{d\sigma/d\Omega}(E_n, \Theta_i)$.

The effect of this averaging can later be reversed by means of the angular resolution function to be considered in the corrections to experimental data. The attenuation factor can similarly be replaced by an average value designated $K_s$, also to be determined later (Appendix C). If the efficiencies $\eta(E_n)$ and the other quantities are known the absolute differential cross section can then be calculated.

The stilbene crystal makes use of the large $(n,p)$ cross section to produce recoil protons which in turn stimulate scintillations in the crystal. Since the pulse height response of stilbene to protons as a function of energy is non-linear a determination of efficiency is difficult. In addition, $\eta(E_n)$ is also affected by relative orientation of the crystal and photoelectric efficiency of the photomultiplier photocathode. Because of these factors it must be replaced by an average value. This average is with respect to energy only since the other parameters remain the same for all angles. When this is done the efficiencies can be eliminated entirely from further consideration by an experimental technique used by Barschall.

By considering the number of neutrons detected in the forward direction ($0^\circ$) with the scatterer removed an expression for this count can be derived in a manner analogous to that above for the scattered neutron count. This relation will also contain the efficiency and if

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the ratio of scattered counts to direct beam counts is taken, the efficiencies as well as several other quantities will cancel. This technique has been used in this lab by other experimenters and a comparison of the results obtained by this method with those obtained by a determination of efficiency by the polythene method for scattering by carbon showed agreement within ±2.5%.

The number of neutrons detected in the forward direction is given by:

\[
N_n^0(\text{detected}) = \sum_t I_d (\text{inc.}) (d\sigma/d\Omega)_{D,d} N_t \Delta t A d\Omega_{td}
\]  
(8)

where \(d\Omega_{td}\) is the solid angle subtended by the detector at the target and the other quantities are those defined earlier. Forming the quotient of scattered detected neutrons to detected neutrons in the forward direction:

\[
\frac{N_n^{sc}(\text{detected})}{N_n^0(\text{detected})} = \sum_t \sum_s \overline{\eta} K_s I_d (\text{inc.}) (d\sigma/d\Omega)_{D,d} N_t \Delta t A_t d\Omega_{td}
\]  
(9)

times \(d\Omega_{ts} d\sigma/d\Omega(E_n, \Theta_i) N_s \Delta t_s d\Omega_{sd} \)

\[
\div \sum_t \overline{\eta} I_d (\text{inc.}) (d\sigma/d\Omega)_{D,d} N_t \Delta t A_t d\Omega_{td}
\]  

the quantities \(N_t, \Delta t, A_t\) and \(\overline{\eta}\) are observed to be constant and can therefore be cancelled. Further, the \(I_d\)'s can be considered to be averaged by the summation and since \(d\Omega_{sd}\) and \(d\Omega_{td}\) are approximately equal, these factors can likewise be cancelled. The resulting expression can then be solved for \(d\sigma/d\Omega(E_n, \Theta_i)\) which is found to be:

\[
\frac{d\sigma}{d\Omega}(E_n, \Theta_i) = \frac{N_n^{sc}(\text{det.})/N_n^0(\text{det.})}{N_n} \sum_t (d\sigma/d\Omega)_{D,d}
\]  
(10)

\[
\div N_s \Delta t_s K_s \sum_s (d\sigma/d\Omega)_{D,d} d\Omega_{ts}
\]
Although a number of simplifying assumptions have been made the pro-
cess of computing the factors in the summations is still lengthy and a
computer program formulated for this purpose by Spahn\textsuperscript{6} was used. This
program was fed to an IBM 7040 at the L.S.U. Computer Center and the
results substituted in the above expression yielding:

$$\frac{d\sigma}{d\Omega}(E_n, \Theta_i) = \left(31.97/7.07\right) \frac{(N_n^{sc}/N_n^O)}{N_s} \Delta t_{sK_s}$$

(11)

The numbers $N_n^{sc}$ are determined by graphing the data tapes from
the H-P Printer for the scattered count and that with the scattered
removed. The presence in the higher numbered channels of the gamma-
peak associated with inelastically scattered neutrons allowed posi-
tioning of the two spectra to account for any shift in spectra when
subtracting the scatterer out count.

Corrections to Experimental Data

It was noted in the preceding analysis that the cross sections
d\(\sigma/d\Omega(E_n, \Theta_i)\) had to be averaged because of the inclusion of scat-
tering at angles other than the desired $\Theta_i$. This averaging process
can be represented as:\textsuperscript{7}

$$\frac{d\sigma}{d\Omega}(E_n, \Theta_i) = \sum_\Theta (d\sigma/d\Omega)_{th}(\Theta) f(\Theta, \Theta_i)$$

(12)

$$= \sum_\Theta f(\Theta, \Theta_i)$$

\textsuperscript{6}C. J. Spahn, "The Compound Elastic Scattering of 3.15 Mev Neu-
trons in Pb," (unpublished Ph.D. dissertation, Department of Physics,
University of Texas, January, 1965).

\textsuperscript{7}P. E. Hodgson, The Optical Model of Elastic Scattering, (Lon-
where \( (d\sigma/d\Omega)_{th} (\theta) \) is the theoretical value of the cross section and \( f(\theta, \theta_i) \) is a quantity called the angular resolution function with respect to which the \( (d\sigma/d\Omega)_{th}'s \) are averaged. Since \( (d\sigma/d\Omega)_{th} \) for each of the different \( \theta_i \)'s is the quantity desired the practical procedure of finding it is to use a trial distribution which gives \( \overline{d\sigma}/d\Omega \). If the values of \( f \) are known at the various \( \theta \)'s about \( \theta_i \) substitution of these values together with the assumed or calculated distribution of the \( (d\sigma/d\Omega)_{th}'s \) should yield the \( \overline{d\sigma}/d\Omega \)'s obtained from experiment. In general, the distribution of \( f \) about \( \theta_i \) will vary with \( \theta_i \) and the calculation of these is given in the appendix (Appendix B).

One method of arriving at a trial \( (d\sigma/d\Omega)_{th} \) is to apply \( f(\theta, \theta_i) \) to the experimentally determined cross section, \( \overline{d\sigma}/d\Omega \). Because of the general form of the elastically scattered angular distribution the effect will be different over different portions of the curve. For instance at angles in the forward direction although the cross section for scattering at small angles is greater than at relatively larger angles, the displacement of the angular resolution function about \( \theta_i \) is such that more of the scattering at angles larger than \( \theta_i \) is included and the net effect is to produce a \( \overline{d\sigma}/d\Omega \) smaller than that measured. As the middle angles (approximately 70-100°) are approached where a minimum in the angular distribution generally appears a cross-over occurs and average values larger than \( \overline{d\sigma}/d\Omega \) are obtained. Thus in the former case if the difference between the experimental value and the \( f \)-determined average is added to the experimental quantity, a value closer to the true \( \overline{d\sigma}/d\Omega \) will follow while for the latter this difference must be subtracted. Continuing this
process for all angles a new distribution will be derived and if iter-
ated a limiting value will be reached which will then be substantially
free of errors due to finite angular resolution for single scattering.

The angular distribution obtained from the above method will
still contain errors due to multiply scattered neutrons which are lost
from the count. As mentioned earlier solution of this problem is ex-
tremely complicated and an analytical technique devoid of approxima-
tions and suitable for all geometries or even for cylindrical geometry
has yet to be devised. Even the Monte Carlo method has been applied
with wide variations in approach and consumes appreciable computer
time as well as demanding some skill as a programmer. Because of
these difficulties the angular resolution corrected cross sections
were not further corrected for multiple scattering.
CHAPTER IV

CONCLUSIONS

Statistics and Resolution

A. Statistics

The experimentally determined and corrected cross sections can now be analyzed for statistical accuracy. The standard error in the cross sections evaluated at each angular setting due to statistical uncertainties requires taking into account the errors in the background (scatterer out) count, direct beam count and the monitoring count as well as the scattered count (elastically scattered neutrons plus background).

The error in the monitoring count is given by the square root of the observed total count since this is assumed to have a Poisson distribution. For the total count for each run used in this experiment:

$$\sigma_m = (192,000)^{\frac{1}{2}} = 438 = \pm 0.2\%$$

In a similar manner the error in the direct beam measurement is found to be in the range:

$$\pm 0.2\% < \sigma_{db} < \pm 0.25\%$$

over the range of counts utilized in this experiment as determined by the monitor count. Since both these errors are small their effect can be overlooked in determining the statistical error in the ratio $\frac{N^s_c}{N^o_n}$. 
With this consideration in mind the error in the ratio averaged for \( k \) runs at each \( \theta_i \) can be obtained and is found to be:

\[
\sigma_r(\theta_i) = \left( \frac{1}{k} \right) (k-1) \sum_{j=1}^{k} \left\{ \frac{N_{ij}^{sc}}{N_n} - \left( \frac{N_{ij}^{sc}}{N_{ij}} \right) \right\}^2 \frac{1}{2}
\]

Substituting the specified quantities in this expression the range of values for the errors is found to vary from 1% in the forward direction to 11% in the back direction (Table III). The larger values are attributable in part to the higher background due to inability to shield the detector sufficiently from target neutrons at the back angles.

B. Resolution

The energy resolution of the spectra \( \Delta E/E_n \) associated with the time resolution \( \Delta t/t_n \) is governed by the relation:

\[
\Delta E/E_n = 2\Delta t/t_n
\]

where \( \Delta E \) is the energy spread associated with neutrons of energy \( E_n \) and \( \Delta t \) is the time spread while \( t_n \) is the time of flight of the neutrons. This latter is given by:

\[
t_n = \frac{72.3d}{(E_n)^{1/2}}
\]

where \( d \) is the flight path in meters and \( E \) is in Mev. Thus:

\[
\Delta E/E_n = \frac{\Delta t(E_n)^{1/2}}{36.15d}
\]

In the present instance \( d \) is 1.25 meters while \( \Delta t \) is the rms value of the following quantities:

- Burst duration ............... 2.5 nanoseconds
- Energy spread of target neutrons ........ 2.2 nanoseconds
- Path in scatterer ............. 0.5 nanoseconds
- Path in detector .............. 1.3 nanoseconds
- Photomultiplier transit time ........ 0.3 nanoseconds
- Recording .................... 0.8 nanoseconds
### TABLE III

**DIFFERENTIAL CROSS SECTIONS (MILLIBARNS PER STERADIAN)**

<table>
<thead>
<tr>
<th>$\theta_{\text{LAB}}$</th>
<th>Al</th>
<th>S</th>
<th>V</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°</td>
<td>679 ± 20</td>
<td>971 ± 10</td>
<td>1388 ± 18</td>
<td>1075 ± 36</td>
</tr>
<tr>
<td>30°</td>
<td>549 ± 4</td>
<td>754 ± 18</td>
<td>1015 ± 14</td>
<td>767 ± 11</td>
</tr>
<tr>
<td>40°</td>
<td>456 ± 3</td>
<td>561 ± 17</td>
<td>693 ± 28</td>
<td>508 ± 7</td>
</tr>
<tr>
<td>50°</td>
<td>329 ± 8</td>
<td>365 ± 4</td>
<td>384 ± 11</td>
<td>243 ± 7</td>
</tr>
<tr>
<td>60°</td>
<td>228 ± 7</td>
<td>227 ± 3</td>
<td>212 ± 2</td>
<td>89 ± 2</td>
</tr>
<tr>
<td>70°</td>
<td>170 ± 4</td>
<td>142 ± 9</td>
<td>117 ± 4</td>
<td>52 ± 1</td>
</tr>
<tr>
<td>80°</td>
<td>137 ± 2</td>
<td>98 ± 7</td>
<td>109 ± 3</td>
<td>65 ± 2</td>
</tr>
<tr>
<td>90°</td>
<td>103 ± 7</td>
<td>65 ± 3</td>
<td>133 ± 4</td>
<td>90 ± 3</td>
</tr>
<tr>
<td>100°</td>
<td>94 ± 9</td>
<td>64 ± 2</td>
<td>151 ± 2</td>
<td>116 ± 8</td>
</tr>
<tr>
<td>110°</td>
<td>90 ± 9</td>
<td>59 ± 4</td>
<td>165 ± 5</td>
<td>119 ± 4</td>
</tr>
<tr>
<td>120°</td>
<td>94 ± 5</td>
<td>65 ± 4</td>
<td>157 ± 6</td>
<td>113 ± 6</td>
</tr>
<tr>
<td>130°</td>
<td>84 ± 8</td>
<td>77 ± 8</td>
<td>147 ± 3</td>
<td>85 ± 10</td>
</tr>
<tr>
<td>140°</td>
<td>105 ± 6</td>
<td>99 ± 4</td>
<td>140 ± 4</td>
<td>70 ± 4</td>
</tr>
</tbody>
</table>
The rms figure of 3.7 nanoseconds gives an energy resolution of 14.5%.

Sources of error other than the counting statistics and temperature effects include machine instability, reproducibility of angular settings and divergence of the deuteron beam at the target to name a few of the more prominent causes not mentioned before. The first of these, machine instability, contributed to the errors primarily through a shift in the spectra caused by fluctuations in the Ion Buncher magnet current. These inaccuracies were kept to a minimum by the previously mentioned warm-up period for the machine plus rejection of the spectra which showed a significant shift when displayed on the CRT of the TMC analyzer.

Angular settings were able to be duplicated to within \( \pm 0.5^\circ \) and since no attempt has been made to correct the abscissae of the measured points for angular resolution this slight inaccuracy will be neglected. Temperature effects were managed as they pertained to the various pieces of equipment in the manner described in earlier sections. The divergence of the deuteron beam as well as all other sources of possible error were considered to be minimal and so dropped from further discussion.

Comparison with Published Data

The differential cross sections were integrated according to the following formula to give the total elastic cross section:

\[
\sigma_{te} = 2\pi \int_\theta (d\sigma/d\Omega) \sin \theta \, d\theta
\]

The integral was evaluated numerically using Simpson's Rule and the list of values so obtained is found in Table IV. Since all the
materials studied have energy levels of the compound nucleus below 3.15 Mev there was some inelastic scattering in each case and the total cross section by an amount depending on the number of levels and the degree of excitation of each. To gain further insight it will be necessary to consider each scatterer in greater detail.

A. Aluminum

The integrated cross section at 3.15 Mev is in good agreement with an expected value of approximately 2 barns obtained by considering the data at 3.01 Mev and 3.25 Mev (Table IV). At 3.25 Mev there is no reported value of the total elastic cross section, however if the total non-elastic figure is subtracted from the total cross section the result is 2.02 barns. Since there is less than a 3% change in \( \sigma_T \) over the range of energies tabulated \( \sigma_{te} \) may be assumed to vary by about the same amount thus giving the nominal value of 2 barns mentioned previously.

A further check on the reliability of angular distribution data can be made by considering Wick's limit\(^1\) for the scattering at 0\(^o\). From other experiments\(^2\) it is found that this limit is approached within a few percent in practice. Using the value of 2.5 b as \( \sigma_T \) this relation gives:

\[
\frac{d\sigma}{d\Omega}(0^0) = (k \sigma_T / 4\pi)^2 = 633 \text{ millibarns}
\]

where \( k \) is the wave number for 3.15 Mev neutrons. The value obtained


TABLE IV

TOTAL, INTEGRATED AND 0° CROSS SECTIONS

<table>
<thead>
<tr>
<th>Scatt.</th>
<th>$E_p$ (MeV)</th>
<th>$\sigma$(total) (barns)</th>
<th>$\sigma$(total elastic) (barns)</th>
<th>$\sigma$(total non-el.) (barns)</th>
<th>$d\sigma/dQ(0^\circ)$ (barns)</th>
<th>Wick’s extrapolated limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scatt.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>2.7</td>
<td>$2.7^a$</td>
<td></td>
<td></td>
<td>$0.650^b$</td>
<td>$0.630$</td>
</tr>
<tr>
<td></td>
<td>3.01</td>
<td>$2.62^c$</td>
<td>$1.98^d$</td>
<td></td>
<td>$0.600^d$</td>
<td>$0.680$</td>
</tr>
<tr>
<td></td>
<td>3.15</td>
<td>$2.5^a,c$</td>
<td>$2.03$</td>
<td></td>
<td>$0.745$</td>
<td>$0.633$</td>
</tr>
<tr>
<td></td>
<td>3.25</td>
<td>$2.55^e$</td>
<td></td>
<td></td>
<td>$0.53^f$</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>2.5</td>
<td>$2.7^c$</td>
<td></td>
<td></td>
<td>$0.54^g$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.7</td>
<td>$3.8^c$</td>
<td></td>
<td></td>
<td>$1.000^b$</td>
<td>$1.250$</td>
</tr>
<tr>
<td></td>
<td>3.15</td>
<td>$2.78^c,h-j$</td>
<td>$1.89$</td>
<td></td>
<td>$1.100$</td>
<td>$0.795$</td>
</tr>
<tr>
<td></td>
<td>3.7</td>
<td>$2.6^k$</td>
<td>$1.80^k$</td>
<td>$0.78^k$</td>
<td>$0.750^k$</td>
<td>$0.804$</td>
</tr>
<tr>
<td>Co</td>
<td>3.15</td>
<td>$3.5^l$</td>
<td></td>
<td></td>
<td>$1.350^k$</td>
<td>$1.232$</td>
</tr>
<tr>
<td></td>
<td>3.7</td>
<td>$3.6^l$</td>
<td>$1.97^k$</td>
<td></td>
<td>$1.400^k$</td>
<td>$1.538$</td>
</tr>
<tr>
<td>V</td>
<td>3.15</td>
<td>$4.0^m$</td>
<td>$2.47$</td>
<td></td>
<td>$1.700$</td>
<td>$1.620$</td>
</tr>
<tr>
<td></td>
<td>3.19</td>
<td>$3.96^m$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* average value
# extrapolated value
TABLE IV - CONTINUED

<table>
<thead>
<tr>
<th>Reference</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>aG. Calvi, R. Potenza, R. Ricamo and D. Vinciguerre, &quot;Nuclear Reactions in Al from 2.5 to 5 Mev,&quot; Nuclear Physics, XXXIX (1962), 621.</td>
<td></td>
</tr>
<tr>
<td>mF. Manero, &quot;Total Cross Sections of V, In, I and Bi for 3.2-5.2 Mev Neutrons,&quot; Nuclear Physics, LXV (1965), 419.</td>
<td></td>
</tr>
</tbody>
</table>
by extrapolation for this experiment is 17% greater than the lower limit. This difference may possibly be explained in part by the unknown contribution of elastic scattering due to compound nucleus formation which would have to be added to the limit to obtain the extrapolated value. It can be noted that the extrapolated $0^\circ$ cross section at 2.7 Mev is only 3% greater than the theoretical value while that at 3.01 Mev is less than its predicted lower bound.

B. Sulfur

The data for sulfur is somewhat sparser than for aluminum however some idea of the expected value for the total elastic cross section can again be inferred from existing data. From the tabulated values for the total cross section it is seen that this quantity varies very little from 3.15 to 3.7 Mev. Consequently one would expect changes in $\sigma_{te}$ to be of the same order as those in $\sigma_T$. If the value of $\sigma_{te}$ at 3.7 Mev is accepted our 3.15 Mev figure is entirely consistent. The total non-elastic cross section increases with energy because of excitation of more energy levels. An interpolation of the values at 2.5 and 3.5 Mev gives a figure of approximately 0.7 barns at 3.15 Mev. This number added to the integrated elastic cross section at the same energy results in 2.59 barns for $\sigma_T$, a quantity smaller than the reported value by less than 8%.

Comparing with Wick's limit the extrapolated cross section at 3.15 Mev is considerably above the calculated value. This may be due in part to a large contribution of compound elastic scattering. There is only one level below 3.15 Mev in $^{32}$S at 2.25 Mev thus the cross section for compound nucleus formation should be fairly large. Since this is undetermined no further conclusions can be drawn.
C. Cobalt

The data here is again sparse, in fact more so than for sulfur. The 3.7 Mev total elastic cross section infers a value greater than that measured at 3.15 Mev because of the decrease of $\sigma_{te}$ with energy as more levels are excited. Since there are no other proximate values little more can be said concerning this. The forward scattering figure obtained in this experiment is in much better agreement with the theoretical limit than either Al or S however this may be because of less compound elastic scattering.

D. Vanadium

In the case of vanadium the data is extremely rare with no differential cross sections below 7 Mev and hence the only point which can be considered qualitatively is the agreement with the 0° limit. The value of 1.7b determined in this experiment again agrees well with the theoretical figure of 1.62b.

A better understanding of the general tendencies can be gained by considering the three dimensional illustration of differential cross sections vs. angle and mass number A (Fig. 12). The data of Singh, obtained under the same general conditions as the data tabulated herein, has been included for completeness. For instance, the sharp increase in the forward scattering for S compared to Al is seen to occur also when comparing Ca$^{40}$ to K$^{39}$. The explanation for the latter is the same as that mentioned earlier, namely, the large

---

FIG. 12—DIFFERENTIAL CROSS SECTIONS vs. $\cos \theta_{cm}$ & $A$
contribution of compound elastic scattering. Ca$^{40}$ has no levels below 3.15 Mev while K$^{39}$ has a number of levels. Although Hauser-Feshbach theory predicts isotropy in the center of mass system for compound elastic scattering the deviation noted can be explained by the contribution of partial waves with angular momentum greater than zero. For 3.15 Mev neutrons incident on K$^{39}$ and Ca$^{40}$ the wave number $k$ is such that waves for which $l = 5$ must be included. These add factors involving the Legendre polynomials of order higher than zero whose effect is not negligible.

The over-all qualitative features follow closely the optical model predictions. For instance, the diffraction pattern of the two higher mass numbered elements (V and Co) show more structure (see Figs. 13-16) than do the lower numbered scatterers as would be expected because of their greater nuclear radii. A related feature is the stronger peaking in the forward direction observed when comparing the former pair with the latter as well as when comparing each member of a given pair with the other member of that pair. In greater detail, the minimum for Co is at a slightly smaller angle than for V; similarly, that for S is smaller than for Al. When comparing these features with those for the same scatterers at nearby energies where data is available the behavior is that expected, namely, a shift of the minimum towards smaller angles and stronger forward peaking. Thus the detailed as well as the grosser aspects of the data obtained in this

---

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Ricamo, R. "Risonanze \((n,n)\) ed \((n,p)\) nel \(^{31}\text{P}\) e \(^{32}\text{S}\)," Nuovo Cimento, VIII (1951), 383.


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APPENDIX A

The calculation of the solid angles and the associated cross sections in the sums in the expression for the differential cross section proceeds from a consideration of the experimental geometry (Fig. 17). The specific quantities of interest are the angle which the radius vector to the representative volume element makes with the direction of the incident deuteron beam and the solid angle subtended at a point P in the target. The analysis here follows that of Singh\textsuperscript{1} but will be repeated for convenience.

For purposes of computation the scatterer was divided along its length into l slices of equal thickness $\Delta X$ while the target was similarly sectioned into $l'$ slices. (For choice of axes see Fig. 17.) Each slice in the scatterer was further divided along the y and z directions into rectangular segments m and n in number, respectively. The resultant volume element of sides $\Delta X_1$, $\Delta Y_{1,m}$, $\Delta Z_n$ forms the representative element mentioned previously. In order to reference these properly in terms of the measured distance from target to scatterer the over-all length from a chosen point P in the target on the axis of the incident beam to the back of the scatterer along this same axis is designated as L. With this notation the distance along the principal axis from P to the center of the slice containing the volume element is:

\[\text{distance} = L - \Delta X_1 - \Delta Y_{1,m} - \Delta Z_n\]

\textsuperscript{1}Singh, op.cit., p. 49.
FIG. 17 — GEOMETRY FOR FLUX CALCULATIONS
\[ X_1 = L - (21 - 1)(\Delta X/2); \quad \Delta X = \text{diameter of scatterer}/I_{\text{max}} \]
\[ = 2R/I_{\text{max}} \]

which is therefore the X-coordinate for all elements in this slice.

The Y and Z directions need only be considered in the positive direction since the angles for the other quadrants are the same. The Z coordinate of an element in this slice is given by:

\[ Z_n = (2n - 1)(\Delta Z/2); \quad \Delta Z = \text{length of scatterer}/2n_{\text{max}} \]

The Y coordinates of the elements in the different slices will not however have the same maximum as one another. These will depend instead on the particular slice and hence \( X_1 \). Therefore, their Y coordinates will have a greatest value of:

\[ Y_1 = (R^2 - |(21 - 1)(\Delta X/2) - R|^2)^{\frac{1}{2}} \]

Consequently:

\[ Y_{1,m} = (2m - 1)(\Delta Y/2) \]
\[ Y_{1,m} = (2m - 1)(R^2 - |(21 - 1)(\Delta X/2) - R|^2)^{\frac{1}{2}}/2m_{\text{max}} \]

From these the radius vector \( r_{1,m,n} \) from P to the volume element can be formed along with its direction cosines. The angle \( \phi \) which this vector makes with the direction of the incident beam is thereby determined and the D(d,n) reaction cross sections associated with this angle and the accompanying deuteron energy at P can be found from Table II. This table is an extension by interpolation of that published in "Fast Neutron Physics - Part I".²

The solid angle subtended by the representative element at P in the direction \( \phi \) about \( r_{1,m,n} \) is given by the area of the face of the

element normal to the incident beam. As a first approximation, neglecting obliqueness with respect to the Y and Z axes this area is:

\[ \Delta A_{1,m,n} = \Delta y \Delta z x_1 / r_{1,m,n} \]

which gives the following for the element of solid angle:

\[ d\Omega_{1,m,n} = \Delta y \Delta z x_1 / r_{1,m,n}^3 \]

In the present case:

\[ m_{\text{max}} = n_{\text{max}} = 4; \quad l_{\text{max}} = 6; \quad l' = 4 \]

The above analysis was carried out with the aim of programming the various factors for computation on the IBM 7040. The resulting values were then substituted in the expressions for the differential cross section.
APPENDIX B

The angular resolution functions for each $\theta_i$ were calculated in a manner analogous to that for the angles of scattering and solid angles in Appendix A with some modifications. In this instance the cylindrical scatterer was approximated by a flat plate divided vertically into strips. To make this assumed geometry more compatible with the real a weighting function proportional to the thickness of the actual scatterer at the various strips was associated with each of these. The width of the plate was then also subdivided horizontally into strips thus forming representative scattering elements. Similarly, the rear face of the target was divided into vertical sections and the scattering angles formed by the mid-point of each target segment with each scatterer element was determined geometrically. This process was repeated for each target segment and the angles so determined were rounded to the nearest degree. The scattering for each of these angles was assumed isotropic in the first approximation. Each angular value was then multiplied by its proper weighting function and the sum of these products for a given angle was tabulated. A plot of these tabulated sums versus scattering angle for a particular $\theta_i$ is then the angular resolution function to be applied.

The number of elements into which the scatterer was divided was 100 while the target was separated into 5 segments. Graphs of several typical distributions are shown in Fig. 18. Again, because of the
FIG. 18 — ANGULAR RESOLUTION FUNCTIONS
tediousness of the computations involved recourse was made to a computer program which then performed the indicated operations.
APPENDIX C

The attenuation factor $K_s$ is calculated by considering the integral:

$$K_s = \frac{1}{x} \int \exp(-n_s \sigma_T X) \, dX$$

where the assumption is made that attenuation of the neutrons in the X direction is much greater than that in either of the other directions and the circular cross section of the scatterer is approximated by a square of area equal to that of the circle. This is done by setting:

$$\pi R^2 = (2D)^2$$

where $D$ is the half-thickness of the simulated scatterer. The origin of coordinates is set at the center of the square and thus the limits of the integral are $(+D)$ and $(-D)$. The variable in the integrand is changed from $X$ to $X + D$ and the expression in the denominator becomes $2D$. 
The author was born in New Orleans, La. on November 22, 1929. He graduated from Jesuit High School in 1947 and entered the U. S. Army in January, 1951. After a tour of duty he was discharged in 1953 and entered Loyola University in New Orleans in September, 1953. Upon graduation in 1957 he was hired by Texas Instruments, Inc. in Dallas, Texas where he worked as a microwave engineer until 1959. In the spring of 1959 he enrolled in the Graduate School of L.S.U. from which he received a Master's degree in Physics in 1961. Since then he has been working towards the Doctor of Philosophy degree for which he is a candidate in the spring of 1966.
Candidate: Roy Anthony Lambert

Major Field: Physics

Title of Thesis: The Differential Elastic Scattering of 3.15 Mev Neutrons by Al, S, V and Co

Approved:

[Signature]
Major Professor and Chairman

[Signature]
Dean of the Graduate School

EXAMINING COMMITTEE:

[Signature]
[Signature]

Date of Examination:

March 7, 1966