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DETERMINATION OF
NON-ELASTIC SCATTERING CROSS SECTIONS
FOR FAST NEUTRONS

by

Herbert Lyndon Taylor

A THESIS
SUBMITTED TO THE FACULTY
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Houston, Texas  April, 1955  O.K. F.V. Bennew
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DETERMINATION OF
NON-ELASTIC SCATTERING CROSS SECTIONS
FOR FAST NEUTRONS

I. Introduction

Attempts have been made for some time to determine the magnitudes of the individual processes of elastic scattering, inelastic scattering, radiative capture, fission, (n, 2n), and other reactions which comprise the total interaction cross section of neutrons. In the energy range of 3 to 15 Mev, which is to be discussed in this paper, the predominant factors of the total cross section are those from elastic and inelastic scattering. This paper is to discuss a method of measuring directly all effects other than elastic scattering, a non-elastic cross section, which is very nearly the cross section for compound nucleus formation.

Early attempts to measure the cross section for inelastic scattering1 used radium-beryllium neutron sources and "threshold" detectors. A "threshold" detector is one in which an element is made into a radioactive isotope by an endoergic reaction with neutrons with

sufficient energy to induce the reaction. Such a reaction must have a negative $Q$ value and thus a threshold energy which the activating neutron must have. Such an experiment was performed by exposing a cylindrical scatterer inside of which was the threshold detector to the neutrons which had passed through 30 cm of lead from the source and comparing the radioactivity induced in the detector when surrounded by the scatterer to an equal exposure of neutrons directly from the source. Such results led, by assuming an exponential absorption, to calculated cross sections which agree within 15% with recent measurements. More recent data\textsuperscript{2,3} have been taken for $^{14}$ LeV neutrons by using threshold detectors and thick spherical shell scatterers in much the same arrangement as for the present work.

Another method for estimating the inelastic scattering cross section has been to determine the neutron spectrum by the exposure of photographic plates to neutrons.\textsuperscript{4,5} This was done by comparison of the tracks


produced in the emulsion for a given neutron energy when the source was surrounded by a sphere of the scatterer to the tracks for the same exposure when the scatterer was not present. The reduction in the number of tracks of neutrons of energy approximately equal to the energy of the neutrons from the source was used to calculate inelastic scattering cross section. The calculation performed assumes the ability to distinguish between elastically and inelastically scattered neutrons by simple energy separation. Comparison of the tracks produced by lower energy neutrons can also show to what energy the neutrons were inelastically scattered. Such measurements made at $1.4$ to $2.5$ MeV$^4$ indicate that for all elements from aluminum to bismuth almost all the inelastically scattered neutrons have an energy of less than $5$ MeV.

These methods involve tedious emulsion studies with a microscope or measuring of induced radioactivity. An improved method was to be desired. Studies at Los Alamos were done at $1.0$ MeV$^6$ by using a high pressure, hydrogen-filled proportional counter as detector, but this was not satisfactory for higher energy neutrons.

---

A detector of the same type as used in this work was also used at 4.0 and 4.5 Mev. The Los Alamos group did the theoretical investigations to show the usefulness of the sphere transmission method. 7, 8

If a monoenergetic source of neutrons was surrounded by a sphere of a material with which the neutrons could interact only by elastic scattering, a biased detector, whose energy discrimination was not sufficiently sharp to resolve the small loss of energy to elastic scattering, would count at the same rate with the scatterer on as with the scatterer off. If, however, the neutrons may be inelastically scattered so that their energy loss renders them incapable of being detected, then they have been effectively absorbed in a transmission experiment which measures the inelastic scattering, and thus in an ideal experiment elastic scattering would produce no loss of counts in the detector.

It is more convenient to place the detector inside the spherical scatterer and allow the scatterer to subtend a small solid angle from a source so that all the neutrons incident on the shell have essentially the


same energy. A general proof for the validity of such an interchange of source and detector has been given by Bethe. 7

The general theory for measuring non-elastic cross sections by transmission of a thick spherical shell has been worked out by Bethe, Beyster, and Carter 3 and has been used in analyzing the experimental results reported herein. The contributions of the present research were to adapt the scintillation type detector to a useful form and to measure the non-elastic scattering cross sections of elements of various atomic weights as a function of energy from 1.5 to 14.1 Mev. The aim of the research was to determine if magic number nuclei behave differently from other nuclei.
II. Apparatus and Equipment

Nuclear reactions induced by particles accelerated in the Rice Institute Var de Graaff accelerator were used as noncenergetic neutron sources. To minimize background effects of neutrons scattered from matter near the source, a minimum amount of material was used at the end of the vacuum tube for the target mounting, and cooling of the target was accomplished by compressed air. The target and the counting apparatus were over a pit which was eight feet deep and covered by a one-quarter-inch aluminum floor.

For 3.5 MeV neutrons the T(p,n)He\(^3\) reaction at zero degrees with respect to the incident beam was used as a source. The target was tritium adsorbed in a zirconium layer which had been evaporated onto a tungsten blank. The particular target used was obtained from Oak Ridge National Laboratories and had a zirconium layer of 1 mg/cm\(^2\). The angular distribution of the T(p,n)He\(^3\) reaction has been measured\(^9\) and the change of energy of the neutrons with angle of emission can be calculated from the usual equation for the energy of a particle emitted in a nuclear reaction. The detector was 4\(^9\)

\(^9\)G.A. Jarvis and J.E. Ferry (private communication).
inches from the source, giving an 80 KeV change in energy at the outer edge of the shell and 12% illumination decrease at the outer edge of the shell.

The D(d,n)He reaction was used as source for the 4.7 KeV and 7.1 KeV neutrons. A gas chamber separated from the Van de Graaff vacuum system by a .0001-inch nickel foil (approximately 2.25 mg/cm²) containing about one-third atmosphere of deuterium gas was used as target. The gas chamber was made of monel metal (2/3 nickel and 1/3 copper) and was 3.0 cm long, 1.1 cm in diameter, and had a beam entrance aperture of 0.0 cm diameter defined by a tantalum plate. The angular distribution of the D(d,n)He reaction has been measured by Jarvis and Perry. The 7.1 KeV data were taken at a distance of 12 inches from the center of the target, giving a 50 KeV decrease in energy at the minimum subtended half-angle and a decrease in illumination of 1%. The detector was placed 16 inches from the center of the target for the 4.7 KeV neutrons. The combined effects of energy change and illumination change were measured experimentally and led to a maximum correction of 7.5% of (1 - e⁻⁻⁻⁻), the number of elastically scattered neutrons, for the uncompensated effect.

10G.A. Jarvis and J.E. Ferry (private communication).
The T(d,n)He$^+$ reaction was used as the source for 12.7 keV and 14.1 keV neutrons. The detector was placed 8 inches from the source at $135^\circ$ to the direction of the incident beam of 675 keV energy to get 12.7 keV neutrons and at $160^\circ$ with respect to the 350 keV beam for the 14.1 keV neutrons.

The scattering samples were thick spherical shells with a standard size of 3 inches (7.62 cm) outside diameter with 2 cm wall thickness. A hole of 5/8-inch diameter through the shell was necessary for the insertion of the counter. The spheres were machined to a tolerance of less than .001-inch from commercially available materials. The one exception to the standard size was the chromium sphere which, was 1.312 inches in outside diameter with a 2 cm wall.

The neutron detectors were of an organic scintillator which gave light pulses from recoil protons caused by neutron scattering in the scintillator.\textsuperscript{11} In such scintillators the light pulse is proportional to the range of the ionizing particle in the scintillator.\textsuperscript{12} It was necessary to make it impossible for gamma-rays which produce Compton electrons to give background pulses of


size comparable to the neutron pulses. To do this the plastic scintillator\textsuperscript{13} was made into spheres of such size that an electron passing through the diameter of the scintillating sphere would give less than half as large a pulse as neutrons from the source. A plastic scintillator was used after discovery that the pulse size in anthracene from neutrons varies as much as 1.5 with the direction of the neutrons. The plastic scintillators did not show directionality of response.

A large volume of scintillator was desirable in the detector to have a high counting rate. For the \textsuperscript{17} and \textsuperscript{18} Hev neutron detector it would have been possible to have a scintillation sphere 2 cm in diameter and still discriminate against gamma-ray pulses. A more practical size to insert into the scattering shells was 1 cm diameter. A 1 cm diameter scintillator was used and was large enough to give an adequate counting rate. The maximum background pulse could be produced in this scintillator by a 2.5 Hev electron, because an electron of greater energy would pass out of the sphere and could not lose all its energy in the sphere. This would give a pulse equivalent to that of a 6 Hev recoil proton.

\textsuperscript{13}Obtained from Nuclear Enterprises, Ltd., 1121 Grosvenor Avenue, Winnipeg, Canada.
An adequate counting rate for the 7.1 MeV data was obtained with a single sphere with a diameter of 6.5 mm. An electron of 1.6 MeV produces a pulse in the scintillator equal to half that from a 7 MeV recoil proton. A 1.6 MeV electron has a range of 6.5 mm in the scintillator.

For the 0.7 MeV neutron detector, it was necessary to use spheres with a diameter of 2.5 mm. The range of a 0.75 MeV electron is 2.5 mm; an electron of this energy produces a pulse 4-5% as large as a 7 MeV proton in the scintillator. A single sphere of 2.5 mm diameter did not give a satisfactory counting rate, so a detector was constructed using four such spheres. Two spheres were placed in each of two layers, the upper layer being supported on a glass disc and positioned so that the spheres were not directly above the sphere in the lower layer. To improve optical coupling and to place electron stopping material between the spheres, the volume of the detector was filled with Kel-F fluid\(^{14}\) \((\text{Cl}_3\text{F}_2\text{C}_6)\). A fluid containing no hydrogen was required to avoid production of recoil protons in the fluid. Such recoil protons would not give so good a pulse size distribution curve because in most instances they would lose

\(^{14}\)Manufactured by W.M. Kellog Co., Chemical Mfg. Div., Jersey City, N.J.
only a fraction of their energy in the scintillator. The minimum distance between the surfaces of two spheres was 5 mm. The minimum energy an electron could have and pass through two spheres and intervening Kel-F was 4 Mev.

The 3.5 Mev neutron detector was constructed of scintillation spheres with a diameter of 1.5 mm. An electron of 0.5 Mev produces a pulse equal to 50% of the pulse from a 3.5 Mev proton and has a range of 1.5 mm in the scintillator. The eight spheres were arranged at quadrant points of each of two layers in a glass tube of 10 mm inside diameter. Spheres in the upper layer were supported by a glass disc and were not directly over the spheres of the lower layer. The sealed volume was filled with Kel-F fluid. Only electrons with energies greater than 3 Mev could traverse two spheres and the minimum intervening material. The 3.5 Mev detector is illustrated in the counter diagram Figure 1. Each of the detector units as described above was constructed on a quartz rod of such a length as to place the geometrical center of the detector at the center of the scattering shell. The detector and quartz were wrapped with .0005 inch aluminum foil and Scotch electrical tape and optically coupled to the
Figure 1: Diagram of Counter Construction
Dumont 6291 photomultiplier tube by silicone vacuum grease.

A cathode follower preamplifier for the photomultiplier tube pulses was connected to the input of an Atomic Instrument Company linear amplifier Model 204-8. The high voltage was supplied by a Scientific Specialties Corporation regulated Power Supply Model FS-22. An Atomic Instrument Company five-channel pulse height analyzer was used to obtain the pulse size distribution.
Figure 2: Pulse height distribution curve for 12.7 Mev neutrons in 1 cm diameter scintillator and pulse height distribution of gamma-rays of maximum effective energy.
Figure 3: Pulse height distribution curve for 3.5 Mev neutrons in eight 1.5 mm diameter scintillators and pulse distribution of gamma-rays of maximum effective energy.
III. Data

When an organic scintillator is exposed to monoenergetic neutrons, a pulse height distribution as given in Figures 2 and 3 will result. Such curves are obtained by plotting the counts in a channel of a differential pulse height analyzer versus pulse height; i.e., pulses in a certain pulse height interval between $E$ and $E + 4E$ versus $E$ for a definite monoenergetic neutron exposure. The number of protons scattered into an energy interval by neutrons is constant for all equal intervals from zero to maximum energy. The pulse height distribution curve is not quite flat, however, since the pulse height depends on the range of the particle producing the pulse and not its energy.

The pulse height distribution curves in Figures 2 and 3 for 12.7 and 3.5 kev neutrons are typical experimental curves which also indicate the relative size of neutron pulses and maximum possible gamma-ray pulses. Theoretically the curve should drop off sharply at the upper end as indicated by the $E_0$ dotted line. Statistical fluctuations in the number of electrons from the photocathode cause the shape of the upper part of the curve to be rounded. The upper end of the theoretical curve
(the \( E_0 \) line of Figures 2 and 3), which crosses the upper end of the pulse height distribution curve at a point half as high as the plateau, is the pulse height of the maximum energy proton recoils. To determine the bias point corresponding to a given neutron energy, the maximum pulse height is multiplied by the ratio of the range of a proton of that energy to the range of a proton of the maximum energy, since the pulse height is proportional to the range of the recoil proton.

When the discriminator bias is set to count all pulses greater than a certain voltage, the counting rate from a constant source will be proportional to the area under the differential pulse height curves for voltages greater than the bias voltage. Such a biased detector does not define a definite, unique energy cut off. Although the energy loss is small from elastic scattering, any loss of energy will reduce the probability that the neutron will be counted in such a biased detector, and the higher the bias, the lower the probability of an elastically scattered neutron being detected. To obtain a high counting rate and to reduce elastic scattering corrections, a low bias is desirable; but a low bias would increase the probability that inelastically scattered neutrons would be counted. In view of these considerations a bias value corresponding to 80% of the energy of the source neutrons
Figure 4: Relative counting rate as function of neutron energy for detector biased at point corresponding to maximum pulses for 3.5 Mev neutrons.
### TABLE I

Summary of Experimental Results

<table>
<thead>
<tr>
<th>Element</th>
<th>Be</th>
<th>C</th>
<th>Al</th>
<th>Ti</th>
<th>Cr</th>
<th>Fe</th>
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</thead>
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<tr>
<td>(N/\text{cm}^2 \times 10^{22})</td>
<td>24.0</td>
<td>16.06</td>
<td>12.37</td>
<td>11.38</td>
<td>16.05</td>
<td>16.91</td>
</tr>
</tbody>
</table>

#### 3.5 MEV

| \(T\) (expt.) | .877 | .832 | .776 | .773 |
| \(T\) (corrected) | .913 | .857 | .813 | .807 |
| \(\sigma_n\) | .68 \(\pm 0.05\) | 1.24 \(\pm 0.05\) | 1.14 \(\pm 0.04\) | 1.14 \(\pm 0.04\) |
| \(\sigma_t\) | 2.40 | 3.67 | 3.90 | 3.47 |
| \(\sigma_n/\pi (R + \lambda)^2\) | .49 | .70 | .62 | .60 |

#### 4.7 MEV

| \(T\) (expt.) | .872 | .828 | .758 | .738 |
| \(T\) (corrected) | .912 | .854 | .797 | .777 |
| \(\sigma_n\) | .70 \(\pm 0.05\) | 1.32 \(\pm 0.06\) | 1.32 \(\pm 0.03\) | 1.38 \(\pm 0.05\) |
| \(\sigma_t\) | 2.20 | 3.40 | 3.70 | 3.72 |
| \(\sigma_n/\pi (R + \lambda)^2\) | .56 | .81 | .78 | .79 |

#### 7.1 MEV

| \(T\) (expt.) | .889 | .848 | .782 | .758 |
| \(T\) (corrected) | .914 | .865 | .809 | .783 |
| \(\sigma_n\) | .74 \(\pm 0.05\) | 1.21 \(\pm 0.04\) | 1.22 \(\pm 0.04\) | 1.35 \(\pm 0.04\) |
| \(\sigma_t\) | 1.88 | 3.18 | 3.50 | 3.44 |
| \(\sigma_n/\pi (R + \lambda)^2\) | .63 | .83 | .81 | .86 |

#### 12.7 MEV

| \(T\) (expt.) | .821 | .892 | .873 | .871 | .810 | .786 |
| \(T\) (corrected) | .871 | .910 | .876 | .873 | .813 | .789 |
| \(\sigma_n\) | .49 \(\pm 0.08\) | .56 \(\pm 1.10\) | 1.06 \(\pm 0.07\) | 1.17 \(\pm 0.06\) | 1.26 \(\pm 0.07\) | 1.36 \(\pm 0.05\) |
| \(\sigma_t\) | 1.60 | 1.30 | 1.69 | 2.37 | 2.60 | 2.67 |
| \(\sigma_n/\pi (R + \lambda)^2\) | .92 | .91 | 1.11 | .91 | .95 | .98 |

#### 14.1 MEV

| \(T\) (expt.) | .855 | .899 | .886 | .872 | .802 | .786 |
| \(T\) (corrected) | .909 | .918 | .890 | .873 | .804 | .788 |
| \(\sigma_n\) | .37 \(\pm 0.08\) | .51 \(\pm 0.08\) | .91 \(\pm 0.05\) | 1.17 \(\pm 0.04\) | 1.33 \(\pm 0.04\) | 1.38 \(\pm 0.03\) |
| \(\sigma_t\) | 1.55 | 1.34 | 1.73 | 2.28 | 2.45 | 2.60 |
| \(\sigma_n/\pi (R + \lambda)^2\) | .72 | .86 | .99 | .94 | 1.02 | 1.02 |

\(\sigma_n\) - non-elastic scattering cross section in barns

\(\sigma_t\) - transmission of scatterer

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<table>
<thead>
<tr>
<th>Cr</th>
<th>Fe</th>
<th>Ni</th>
<th>Cu</th>
<th>Ag</th>
<th>Sn</th>
<th>Fo</th>
<th>Bi</th>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.05</td>
<td>16.91</td>
<td>18.18</td>
<td>16.90</td>
<td>11.72</td>
<td>7.40</td>
<td>6.59</td>
<td>5.62</td>
</tr>
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3.5 MEV

| .776 | .773 | .717 | .734 | .758 | .845 | .876 | .883 |
| .813 | .807 | .747 | .767 | .775 | .857 | .891 | .896 |
| 1.14 ± .04 | 1.14 ± .04 | 1.48 ± .04 | 1.45 ± .04 | 2.03 ± .07 | 2.00 ± .09 | 1.58 ± .07 | 1.73 ± .06 |
| 3.90 | 3.47 | 3.35 | 3.45 | 4.18 | 4.28 | 7.70 | 7.76 |
| .62 | .60 | .76 | .72 | .81 | .73 | .44 | .48 |

4.7 MEV

| .758 | .738 | .703 | .704 | .749 | .826 | .831 | .848 |
| .799 | .777 | .741 | .737 | .769 | .838 | .851 | .867 |
| 1.32 ± .03 | 1.38 ± .05 | 1.54 ± .06 | 1.69 ± .04 | 2.14 ± .07 | 2.33 ± .07 | 2.25 ± .07 | 2.39 ± .06 |
| 3.70 | 3.72 | 3.55 | 3.72 | 4.01 | 4.00 | 7.40 | 7.48 |
| .78 | .79 | .87 | .91 | .88 | .92 | .66 | .70 |

7.1 MEV

| .782 | .758 | .743 | .754 | .770 | .844 | .825 | .851 |
| .809 | .783 | .770 | .779 | .782 | .851 | .833 | .857 |
| 1.22 ± .04 | 1.35 ± .04 | 1.33 ± .06 | 1.37 ± .05 | 2.01 ± .07 | 2.12 ± .06 | 2.67 ± .07 | 2.66 ± .07 |
| 3.50 | 3.44 | 3.60 | 3.73 | 4.12 | 4.08 | 5.60 | 5.60 |
| .81 | .86 | .84 | .82 | .91 | .92 | .85 | .84 |

12.7 MEV

| .810 | .786 | .773 | .768 | .806 | .860 | .842 | .867 |
| .813 | .789 | .776 | .771 | .808 | .861 | .843 | .868 |
| 1.26 ± .07 | 1.36 ± .05 | 1.35 ± .05 | 1.49 ± .05 | 1.75 ± .10 | 1.97 ± .09 | 2.58 ± .09 | 2.47 ± .14 |
| 2.60 | 2.67 | 2.83 | 3.10 | 4.41 | 4.61 | 5.15 | 5.05 |
| .95 | .98 | .96 | 1.01 | .88 | .94 | .90 | .86 |

14.1 MEV

| .802 | .786 | .761 | .777 | .804 | .870 | .843 | .866 |
| .804 | .788 | .763 | .779 | .806 | .871 | .844 | .867 |
| 1.33 ± .04 | 1.38 ± .03 | 1.45 ± .05 | 1.44 ± .04 | 1.78 ± .05 | 1.82 ± .06 | 2.52 ± .09 | 2.50 ± .07 |
| 2.45 | 2.60 | 2.72 | 2.96 | 4.34 | 4.68 | 5.48 | 5.46 |
| 1.02 | 1.02 | 1.05 | 1.00 | .91 | .88 | .89 | .88 |

---

*Cross section in barns*

C_t - total scattering cross section in barns

R = 1.4 x 10^-13 A^2 cm
was used for the cross section determination at 12.7 and 14.1 Mev and a value of 85\% at 3.5, 4.7, and 7.1 Mev.

To determine the rate at which the probability of detection decreased with energy, the efficiency of detection as a function of energy was measured for each detector. The curve for the 3.5 Mev neutron detector is shown in Figure 1. Such a curve was obtained by biasing the detector at the same point as used in the experiment and plotting the number of counts for a specific number of source neutrons versus neutron energy. The curves for efficiency of detection for the other neutron energies were almost identical in shape with Figure 1.

The data of this experiment for cross section determination were taken by setting one bias of the pulse height analyzer to correspond to 80\% or 85\% of the source neutron energy, as discussed above, and measuring counting rates with the scatterer both in position and removed from position. The ratio of the counting rate with the scatterer in position to the counting rate without the scatterer is the experimental transmission. The transmissions given in Table I are a mean of 6 to 20 separate experiments. Simultaneously with the 80\% or 85\% bias, a lower bias transmission was taken to indicate the dependence of the transmission on the choice of bias point.
At 12.7 Mev a bias point corresponding to 57% of the source neutron energy gave cross sections which were an average of only 4% smaller than for the 80% bias. This result would indicate that only 4% of the inelastically scattered neutrons have an energy between 7.2 and 16.2 Mev. A neutron of 9.1 Mev had a 50% probability of being detected by the bias discriminator set at 90% of the energy for 12.7 Mev neutrons. The average per cent decrease in cross section for copper and lighter elements was 2.7% and for silver and heavier elements 5.6%. This difference is not statistically very significant, but, if significant at all, would indicate that there are more 7 to 10 Mev inelastically scattered neutrons in heavy nuclei than light nuclei.

At 1.7 Mev, data were taken with a bias of 70% as well as 15% of the energy. The average decrease in cross section at 70% bias was 4%, indicating about 4% of the neutrons inelastically scattered to energies between 2.9 and 3.3 Mev. Silver is the only element with energy levels below about 1 Mev. The probability of detection of 1.1 Mev neutrons was 50%. Therefore, neutrons exciting levels of 0.6 Mev or less would contribute less than 50% of their cross section to the observed value. Neutrons exciting the 0.345 Mev level of iron would contribute 85% of their effect.
At 3.5 Mev a bias at 57% of the energy as well as the 85% bias was taken. The average per cent decrease in cross section was 6% for the elements titanium through bismuth. Neutrons of 3.1 Mev are counted with efficiency of 50%. A loss of energy of 0.315 Mev gives the neutrons only 2% probability of being detected.

The errors from counting inelastically scattered neutrons are rather small, and the given transmissions approach fairly closely the true non-elastic transmission, although they are really upper limits to the actual transmission. The probable errors of the non-elastic cross sections given in Table I include an allowance for systematic errors in addition to the error estimated from the deviation of the individual transmission experiments from their mean.

The transmissions must be corrected because of (1) the uncompensated elastic scattering due to the decreased efficiency of detecting the elastically scattered neutrons of slightly less energy, (2) the spread in energy of the neutrons from the source at the scatterer which produces a small change in the counting efficiency, and (3) the non-uniform illumination of the spherical scatterers.

The detector for neutrons of 3.5, 4.7, and 7.1 Mev was placed at zero degrees with respect to the direction
Figure 5: Diagram of scatterer at zero degrees from neutron source showing relation of angle of emission from source and elastic scattering angle.
of the accelerator beam on the target and subtended a very small solid angle at the source as indicated in Figure 5. Thus the neutrons detected when the scatterer was not in position were emitted from the source at essentially zero degrees. When the scatterer was in position, some neutrons did not reach the detector because of elastic scattering in the portion of the shell directly between the source and detector, at point A in Figure 5. The number of those elastically scattered neutrons is assumed to equal (except for small corrections) the number of neutrons elastically scattered towards the detector by the rest of the spherical shell. Such elastically scattered neutrons will not have exactly the same energy as the incident neutrons and, as indicated by Figure 4, will not have the same probability of being detected. The fraction of the incident neutrons so scattered is \(1 - e^{-N\sigma_e}\), where \(N\) is the number of nuclei per square centimeter of the scatterer and \(\sigma_e\) is the elastic scattering cross section. Since only the total scattering cross section \(\sigma_t\) was available for all energies, an assumed value of non-elastic scattering cross section \(\sigma_n\) was subtracted from \(\sigma_t\) to obtain \(\sigma_e\). When necessary, in view of later calculations, the assumed \(\sigma_n\) was revised. The energy lost by a neutron depends on the angle through which it was scattered. The number of elastically scat-
tered neutrons as a function of angle of scattering is

\[ N_\theta = \int \frac{d\sigma(\theta)}{d\omega} \ N(\omega) \ d\omega \]  (1)

where \( \frac{d\sigma(\theta)}{d\omega} \) - differential elastic scattering cross section at angle \( \theta \)

\( N(\omega) \) - number of scattering nuclei per unit area in an element of solid angle

\( d\omega \) - the element of solid angle a scattering element subtends at the detector.

For spherical shells \( N(\omega) \) is a constant. The dependence of the number of scattered neutrons and the energy of the scattered neutrons on the azimuth angle is constant. It is then only necessary to be concerned with the fact that the number of neutrons elastically scattered is proportional to

\[ \int \frac{d\sigma(\theta)}{d\omega} \sin \theta \ d\theta = N_\theta \]  (2)

where \( \theta \) is the elastic scattering angle. The average energy loss of the elastically scattered neutrons which reach the detector is

\[ \frac{1}{N_\theta} \int \frac{d\sigma(\theta)}{d\omega} \Delta E(A,\theta) \sin \theta \ d\theta = E_a \]  (3)

where \( \Delta E(A,\theta) \) is the energy lost by a neutron elastically scattered off a nucleus of mass \( A \) at an angle \( \theta \). The fraction of these neutrons counted is read from the efficiency curve of the detector (Figure 1 for 3.5 MeV detector).
For an efficiency of \( p \), there are \((1 - p)\) times the number of elastically scattered neutrons fewer counts recorded with the scatterer in position than should have been recorded if the spherical geometry were to completely cancel the effects of elastic scattering. Therefore, the correction to the transmission for the elastic scattering energy loss is

\[
C_{e1} = (1 - e^{-\sigma e}) (1 - p). \quad (1)
\]

The assumption is made that the same fraction of first scattered neutrons is elastically scattered again as incident neutrons are first scattered. Then the correction to the transmission for elastic second scattering is

\[
C_{e2} = (1 - e^{-\sigma e})^2 (1 - p). \quad (5)
\]

Error introduced by this assumption is small, because the correction is very small, about \(1\%\) of the elastically scattered neutrons.

Because of center-of-mass motion of the reaction producing the neutrons, the energy of neutrons emitted at zero degrees is more than the energy of neutrons emitted at a non-zero angle \( \phi \). Thus neutrons which illuminated the outer portions of the scatterer did not have quite so high an initial energy as the neutrons detected at zero degrees without the scatterer. As illustrated in Figure 5,
an angle of emission $\phi$ can be approximately related to scattering angles $\theta$ and $\pi - \theta$. Then the difference of emission energy of a source $S$ is written as a function of the scattering angle, the average energy by which neutrons elastically scattered towards the detector fall below the maximum energy from source energy spread is

$$\frac{1}{N_e} \int \frac{d\sigma(\varepsilon)}{d\omega} \Delta E(S, \theta) \sin \phi d\theta$$

(6)

The fractional counting loss ($1 - p'$) corresponding to that energy decrement is again determined from the efficiency curve. If the sum of average energy loss from elastic scattering and average decrease from the maximum energy from the source energy spread is so large that the final neutron energy is lower than the linear portion of the efficiency curve (near the arrow on Figure 4), the efficiency corresponding to the sum of the average energy decrements must be used rather than the sums of the effects calculated individually.

The fact that the source is not isotropic adds yet another correction from elastic scattering. There are not so many neutrons emitted at non-zero angles as at zero. Hence, there can not be so many neutrons elastically scattered into the detector as scattered out by the section of the sphere at A in Figure 5. To compensate for this effect, the loss of illumination of the sphere is
related to the scattering angle (as for the energy loss above). Then the average counting loss is

$$\frac{1}{\sin \theta} \int \frac{d\sigma(\theta)}{d\Omega} \Delta E(S, \theta) \sin \theta \, d\theta = I'$$

(7)

For the case where energy losses are so small that the linear portion of the efficiency curve is not exceeded, the corrected transmission would be

$$T_c = T(\text{expt}) \times C_{e1} \times C_{e2} \times (1 - e^{-\sigma e}) (1 - p')$$
$$\times (1 - e^{-\sigma e}) = I'$$

$$= T(\text{expt}) \times (1 - e^{-\Delta E}) \left[ (1 - p) \times (1 - e^{-\sigma e})(1 - p) \times (1 - p) \times I' \right]$$

(8)

because the detector was not placed at zero degrees from the target for the 15.7 and 24.1 MeV data, the small change in energy and illumination required no correction. The small change in energy and illumination of the source at angles slightly different from the mean angle was positive to one side of the mean angle and very nearly equally negative to the opposite side of the mean angle.

A study of elastic scattering in sufficient detail to include angular distributions of all the elements studied here at all the energies has not been made. Data
at 1 MeV\textsuperscript{15}, 4.0 MeV\textsuperscript{16}, and 14 MeV\textsuperscript{17} for several elements are available. Where angular distribution data for an element studied in this work were not available, the distribution for the element of nearest atomic weight available was used. The 4.0 MeV angular distributions were used for the 3.5 MeV and 1.7 MeV data. The 14 MeV angular distributions were used for the 12.7 and 14.1 MeV data. The 4 and 14 MeV angular distributions are somewhat similar in that they both show large values for small angles, and the difference in magnitude of differential cross section at any particular angle would be expected to come from a smooth variation with energy. Therefore, since no angular distributions were available near 7 MeV, the effects expected from both 4.0 MeV and 14 MeV angular distributions were calculated for the 7.1 MeV data and a linear interpolation made to get the effect expected from 7.1 MeV angular distributions. The errors introduced by this approximation are quite small. In the case of lead the correction for source energy spread and illumination is 3.7\% of \((1 - e^{-10\sigma g})\) with 4.0 MeV angular distributions, 1.4\% with 14 MeV distributions, and 3.0\% for the interpolated value at 7.1 MeV.

\textsuperscript{15}H. Walt and H.E. Barschall, Phys. Rev. 22, 1062 (1\textsuperscript{3}54).

\textsuperscript{16}H. Walt (private communication).

\textsuperscript{17}J. Coon (private communication).
A preliminary check was made to determine the effect of the finite distance from source to detector. The transmission of the copper sphere varied from 0.776 at 5.7 cm from the 14 Mev source to 0.785 at 13.5 cm from the source. This indicates that any effect is small, but the present trend is opposite to that predicted by Bethe. Data published by Phillips, et. al., also show an effect opposite to Bethe's prediction. No correction for detector distance has been applied to this data; most of the data were at distances greater than 10 cm.

The non-elastic cross sections were then calculated from an expression derived by Bethe, Leyster, and Carter which takes account of multiple scattering in the shell.

\[
(1 - T) = (1 - T_0) \frac{\Sigma_n}{\Sigma_n + \Sigma_{et} P_m} 
\]

(3)

where \(T\) - experimental transmission (corrected)

\(T_0\) - \(e^{-\Sigma E}\)

\(P_m\) - escape probability of the neutron

\(\Sigma_n\) - non-elastic cross section

\(\Sigma_e\) - elastic cross section

\(\Sigma_{et}\) - elastic transport cross section

\[
S = \frac{\int \sigma_e(\theta) (1 - \cos \theta) d\theta}{\int \sigma_e(\theta) d\theta} 
\]

(10)
Relation (9) allows a simple physical interpretation. The total number of neutrons which are "supplied" to the shell is \((1 - T_0)\). These can be removed from the shell by two processes, either by non-elastic scattering, or by escape. In a given collision, the probability of non-elastic scattering is \(\sigma_n\), and that of elastic scattering followed by escape is \(\sigma_{\text{el}}\). This gives the fraction scattered non-elastically.

To use this formula it is necessary to assume a value of \(\sigma_n\) and use it in the equation. The non-elastic cross section \(\sigma_n\) is subtracted from the known \(\sigma\) to determine \(\sigma_e\). The \(\sigma_m\) values have been calculated by Rethe, seyham, and Carter, and in this experiment had values which extended from \(0.05\) to \(0.1\). A trial and error process of successive approximations is necessary to achieve the final result.

The present data and the recent work of Heyster, Henkel, and Yole, giving \(\sigma_n\) versus neutron energy, are given in Figures 6-9.
Figure 6
Figure 7
Figure 8
Figure 9
IV. Discussion

The curves for non-elastic scattering cross section given in Figures 6-9 were drawn smoothly through the data. The data give no indication that the non-elastic scattering cross section has nearly so much resonance structure as the elastic scattering cross section. The elastic scattering curve was obtained by subtracting the non-elastic scattering cross section curve from a curve of the best total cross sections that are available\textsuperscript{12}, \textsuperscript{14}, \textsuperscript{20}, \textsuperscript{21}.

Comparison of the measured non-elastic cross section to the geometrical cross section is shown in Table I. For calculating \( R \), the constant \( k \) assumed was \( 1.4 \times 10^{-11} \) cm, where \( R = kA^{\frac{3}{2}} \). Another approach can be made using Table II, which is a tabulation of \( k \) calculated from a mean of the \textsuperscript{12.7} and \textsuperscript{14.1} MeV non-elastic cross sections assuming unit sticking probability. One immediate conclusion which can be drawn is that the constant \( k \) must be greater than

\textsuperscript{18}Morris Hereson and Sperry Darden, Phys. Rev. \textbf{86}, 775 (1952) and private communication.

\textsuperscript{19}Neutron Cross Sections AECL - 2040 and 3 supplements.


TABLE II

The constant $k$ in $10^{-13}$ cm calculated from high energy data assuming unit sticking probability, where $R = ka^2$.

<table>
<thead>
<tr>
<th>Element</th>
<th>$k$</th>
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<tbody>
<tr>
<td>Se</td>
<td>1.35</td>
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<tr>
<td>C</td>
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<tr>
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<tr>
<td>Ni</td>
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</tr>
<tr>
<td>Cu</td>
<td>1.40</td>
</tr>
<tr>
<td>Ag</td>
<td>1.31</td>
</tr>
<tr>
<td>In</td>
<td>1.32</td>
</tr>
<tr>
<td>Pb</td>
<td>1.31</td>
</tr>
<tr>
<td>Si</td>
<td>1.29</td>
</tr>
</tbody>
</table>
1.4 x 10^{-13} \text{ cm}, since the sticking probability is less than unity.

Comparison of non-elastic cross section and elastic cross section at 12 to 14 \text{ Mev} indicates that there may be an interference of waves entering the nucleus, suffering only a phase change without stronger interactions, and then interfering with the incident waves. At 14.1 \text{ Mev} for aluminum, chromium, iron, and nickel, the ratio $\sigma_n/\pi(R + \lambda)^2$ is greater than one. At this energy these elements have an elastic cross section which is less than the non-elastic cross section. Similarly, it is noticed that for lead and bismuth at 14 \text{ Mev} the $\sigma_n/\pi(R + \lambda)^2$ ratio is particularly low, and the elastic cross section is greater than the non-elastic cross section. Both these results can be explained by interference effects of different phase shifts. If this explanation is correct for the low ratio $\sigma_n/\pi(R + \lambda)^2$ for the heavier elements at 14 \text{ Mev}, then the constant $k$ is probably not less than 1.4 x 10^{-13} \text{ cm}.

When the 12.7 \text{ Mev} data were taken, one of the five channels of the pulse height analyzer was set to count pulses with heights between 10 and 14 \text{ volts}, as indicated by dotted lines on Figure 2. Some of these pulses were produced by gamma-rays with energy greater than 2 \text{ Mev}. This channel corresponded to neutrons with energies of from 5.2 to 6.3 \text{ Mev}. Since the results of Graves and Rosen
Figure 10: Relative number of observed gamma-rays of minimum of 2.5 Mev from inelastic scattering.
show that there are very few inelastically scattered neutrons of this energy, any increase in the counts in this channel with the sphere in position are due to gamma radiation produced in the scatterer. There were more counts in this channel for many elements with the scatterer on than with the scatterer off. This increase in counting above the expected neutron counts was attributed to gamma-rays produced by the inelastic scattering in the sphere. The ratio of gamma counts to the neutron absorption \((1 - T)\) is plotted as a function of atomic weight in Figure 10.

The fact that more gamma-rays are observed for lighter elements than for the heavier ones is easily explained by the fact that \((n,2n)\) reactions have higher cross sections for heavier elements and comprise a greater portion of the non-elastic cross section than for the lighter elements. The \((n,2n)\) \(Q\) value influences the magnitude of the \((n,2n)\) reaction, particularly for elements of approximately the same atomic weight. Table III gives a number of the \(Q\) values. It is rather difficult to understand such a rapid decrease in the number of gamma-rays from nickel and copper in comparison to chromium and iron, particularly in view of the comparatively small change in \(Q\) for \((n,2n)\) of 11.8 kev for Cr\(^{52}\) to 17.6 kev for Cu\(^{63}\). The low number of gamma-rays from nickel is particularly difficult to explain,
### TABLE III

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Relative abundance</th>
<th>Q(keV)</th>
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</thead>
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<td>Ti 50</td>
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<tr>
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<td>Ni 60</td>
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</tr>
<tr>
<td>Pd 208</td>
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<td>-7.38</td>
</tr>
<tr>
<td>Ti 209</td>
<td>100</td>
<td>-7.28</td>
</tr>
</tbody>
</table>

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unless the \((n,2n)\) Q value of \(^{68}\text{Ni}\) is less than the reported value of 11.7 Mev.

The shape characteristics of the elastic scattering cross section versus energy curves appear to vary smoothly with atomic weight. A rapid decrease from a plateau appears to move to higher energies from aluminum at 6 Mev, to titanium at 7 Mev, and to chromium at 9 Mev. A minimum appears in the elastic cross section at 1.5 Mev in nickel and in copper. A broad peak in elastic cross section appears to move from 5 Mev in iron, to 6.2 Mev in nickel, and to 6.3 Mev in copper. For silver and tin the broad peak becomes much broader and looks as if it may have a maximum at about 11 to 12 Mev in silver and at about 14 to 15 Mev in tin. The minimum for elastic scattering in silver at 4.7 Mev and in tin at 5.2 Mev appears to have moved up to 9.3 Mev in lead and 3.5 Mev in bismuth. Lead and bismuth exhibit comparatively sharp peaks in elastic cross section at 3.4 Mev. These variations of elastic scattering cross sections with atomic weight appear to fit qualitatively the predictions of the Weisskopf "cloudy crystal ball" model\(^{23}\), \(^{24}\) in which the location of wide

\(^{23}\) H. Feshbach, C.E. Porter, and V.F. Weisskopf, Phys. Rev. 90, 166(L) (1953).

resonances appears as a function of the nuclear radius. In this model the nuclear potential is taken as a complex square well of the form $V = V_0(r) (1 + i\delta)$, where $i = \sqrt{-1}$ and $\delta$ is some real number which gives the absorption necessary to account for the formation of a compound nucleus. In a paper by Feshbach, Porter, and Weiskopf, the total cross sections have been fitted up to about 3 mev with this model using a $\delta$ equal to .03. To get the observed large value of the cross section for compound nucleus formation it will be necessary to make $\delta$ larger and to make it a rapidly varying function of energy above 1 mev. For neutrons with energies above 1.7 ev there seem to be no significant differences in the non-elastic cross sections which can be attributed to magic number nuclei (tin, lead, and bismuth).
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