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INELASTIC COLLISON CROSS SECTIONS OF VARIOUS ELEMENTS FOR 14 MEV NEUTRONS

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INELASTIC COLLISION CROSS SECTIONS OF VARIOUS ELEMENTS FOR 14 MEV NEUTRONS

DISSERTATION

Presented to the Faculty of the Graduate School of
The University of Texas in Partial Fulfilment
of the Requirements
For the Degree of
DOCTOR OF PHILOSOPHY

By

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Austin, Texas

June, 1949

PREFACE

This dissertation is based on work performed at Los Alamos Scientific Laboratory of the University of California. It was made possible by the decision of the Laboratory and the Atomic Energy Commission to allow certain graduate students from various western universities and colleges to come to Los Alamos to use the facilities of this laboratory in doing research toward th Ph. D. degree. It was through the participation of the University of Texas in this plan that the author was able to take advantage of this opportunity.

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Donald Davis Phillips

April 1, 1949

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CHAPTER I

INTRODUCTION

Neutron scattering experiments furnish one of the best methods of obtaining information about the nucleus, such as its size and inter-nuclear forces. The very characteristic (lack of charge) which makes neutrons difficult to control and to detect accounts for their big advantage in nuclear research. Since they are uncharged, they do not experience strong long range or coulomb forces such as are experienced by charged particles approaching nuclei.

The cross section of a nucleus is the effective area which it presents to a bombarding particle such as a neutron. For slow neutrons this effective area may become very large and show strong resonances. For neutron energies of several Mev and more, cross sections become much smaller and vary in such a way with the atomic weight of the bombarded nucleus as to suggest a simple relation between observed cross sections and the geometrical dimensions of nuclei.

We shall speak of inelastic collisions as those collisions between neutrons and nuclei from which a neutron does not emerge with as much energy as would be predicted by conservation of momentum and kinetic energy. The compound nucleus may emit a neutron of lower energy, or it may emit an entirely different particle or perhaps a gamma ray. If a high energy neutron actually penetrates a nucleus to form a compound nucleus, it is highly improbable that it will be emmited with its initial energy. Inelastic collision cross sections of heavy nuclei for fast neutrons therefore should be essentially the geometric cross sections of those nuclei plus the effective cross section of the neutron.

There are in the literature* many articles describing measurements of total cross sections as well as inelastic cross sections of nuclei for neutrons of different energies. One big trouble in the past has been the lack of sources of really monoenergetic fast neutrons. Some authors have used Ra-Be neutron sources which show a practically continuous energy spectrum up to about 14 Mev. Some measurements of inelastic collision cross sections have suffered from difficulty in separating effects due to elastic scattering.

The method used by the author for eliminating, or at least minimizing, the effects of elastic scattering is described in Chapter II. The neutron source, which had very little energy spread, is described in Chapter III.

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*See Bibliography.

CHAPTER II

SPHERE SCATTERING AND THRESHOLD DETECTORS

Consider a spherically symmetrical source of Q neutrons per second. The flux at a distance r is $Q/4\pi r^2$. We wish to take up two cases. Case I is that case in which the neutron source is at the center of a sphere of scattering material and a small neutron detector is placed outside the sphere. In Case II we shall consider the source and detector to be interchanged so that the detector is at the center of the sphere and the source is outside.

Case I. The source of Q neutrons per second is at the center of a sphere of heavy material. Let the radius, R, or thickness of this sphere be of the order of one-half the mean free path for the neutrons coming from the source. Suppose for the sake of argument that only elastic scattering exists and that the atoms of the sphere are heavy enough that a neutron loses a negligible fraction of its energy in one collision. Since all neutrons eventually get out of the sphere, an equilibrium condition will soon be reached where there are just as many neutrons leaving the sphere per second as are produced by the source at the center. The sphere now behaves as a neutron source emitting Q neutrons per second. The number of neutrons per second passing out of any spherical shell of radius, $r > R$, is also Q. Therefore since nothing has been done to destroy the spherical symmetry the number of neutrons crossing unit area at a distance, r, is $Q/4\pi r^2$, which is the same as when no scattering sphere was used. This means that the number of neutrons prevented by scattering from passing through a small area of the shell at a distance, r, from the source is the same as the number of neutrons scattered into this small area from parts of the sphere not on a straight line between source and detector. Actually this causes an increase in the neutron density or an increase in the number of neutrons passing through a spherical detector of finite radius. This we shall refer to as the obliquity effect. It is not serious (as will be shown later) except when the distance from source to detector is only slightly greater than the radius of the sphere.

Case II. Now let us suppose the source and detector to be interchanged so that the detector is at the center of the sphere and the source outside. Without the sphere, the flux at the detector will be $Q/4\pi r^2$ as before. There are the same number of neutrons per second in the direct beam from source to detector as before. Each neutron traverses the same thickness of scatterer and therefore has the same probability of being scattered as before. Consequently the same number of neutrons per second will be scattered out of the direct beam as in Case I.

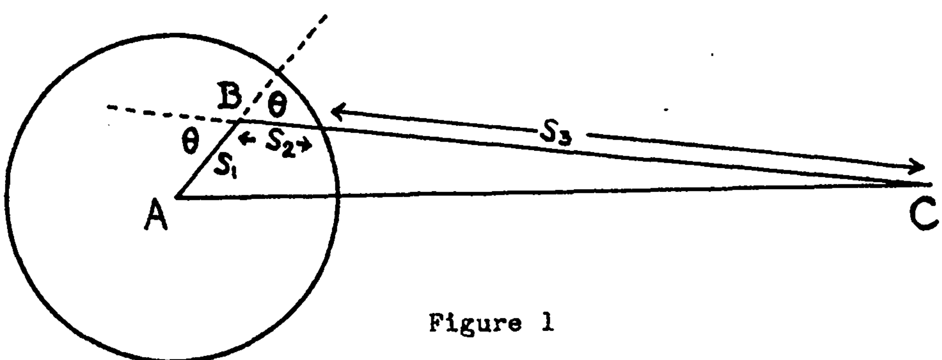


Figure 1

Now let us consider the relative probabilities of a neutron going from source to detector by path ABC and by path CBA of Figure 1. Let the cross section for elastic scattering through an angle θ be $\sigma(\theta)$, and let $r_D/(S_2 + S_3) = \sin \Delta\theta_2$, where r_D is the radius of the detector. Then the probability that a neutron after leaving A (Case I) will be scattered through an angle $\theta \pm \Delta\theta_2$ by a heavy nucleus at B is

$$\frac{\exp(-S_1 N \sigma) \int_{\theta - \Delta\theta_2}^{\theta + \Delta\theta_2} \sigma(\theta) 2\pi \sin\theta \, d\theta}{4\pi S_1^2}$$

Where N is the number of scattering atoms per unit volume and σ is the total cross section,

$$\sigma = \int_0^{\pi} \sigma(\theta) \, 2\pi \sin\theta \, d\theta.$$

The probability of a neutron which has been scattered through an angle $\theta \pm \Delta\theta_2$ at B reaching the detector of radius, r_D, located at C is

$$\frac{\exp(-S_2 N\sigma)\pi r_D^2}{2 r_D \, 2\pi(S_2 + S_3)\sin\theta}$$

or

$$\frac{\exp(-S_2 N \sigma) \, r_D}{4(S_2 + S_3) \sin\theta} .$$

Therefore the probability of a neutron leaving a spherically symmetrical source at A and reaching a detector at C by traveling along the path ABC is

$$P_{ABC} = \frac{\exp\left[-N\sigma(S_1 + S_2)\right] r_D \int_{\theta - \Delta\theta_2}^{\theta + \Delta\theta_2} \sigma(\theta) \, 2\pi \sin\theta \, d\theta}{16\pi S_1^2 (S_2 + S_3) \sin\theta}$$

Now consider Case II where the source is at C and the detector is at A. The probability that a neutron after leaving C will be scattered through an angle $\theta \pm \Delta\theta_1$ by a heavy nucleus at B is

$$\frac{\exp\,(-S_2\, N\sigma)\displaystyle\int_{\theta-\Delta\theta_1}^{\theta+\Delta\theta_1} \sigma(\theta)\; 2\pi \sin\theta \; d\,\theta}{4\pi(S_2 + S_3)^2}$$

where $\Delta\theta_1$ is defined by $\sin\Delta\theta_1 = r_D/S_1$. The probability of a neutron which has been scattered through an angle $\theta \pm \Delta\theta_1$ at B reaching the detector at A is

$$\frac{\exp\,(-S_1\, N\sigma)\pi r_D^{\;2}}{2r_D\; 2\pi S_1 \;\sin\theta}$$

or

$$\frac{\exp\,(-S_1\, N\sigma)\; r_D}{4\; S_1\;\sin\theta}\;.$$

The probability of a neutron leaving a spherically symmetrical source at C and reaching a detector at A by traveling along the path CBA is

$$P_{CBA} = \frac{\exp\left[-N\sigma(S_1 + S_2)\right] r_D \displaystyle\int_{\theta-\Delta\theta_1}^{\theta+\Delta\theta_1} \sigma(\theta)\; 2\pi \sin\theta\; d\,\theta}{16\pi S_1\;(S_2+ S_3)^2\;\sin\theta}\;.$$

It is not obvious that $P_{CBA} = P_{ABC}$.

Let us consider the case where $\sigma(\theta)$ is a constant,

$$\sigma = \int_0^{\pi} \sigma(\theta)\; 2\,\pi \sin\theta\; d\,\theta = -\,2\pi\sigma\,(\theta)\;\Big[\cos\theta\Big]_0^{\pi} = 4\pi\sigma(\theta),$$

$$\int_{\theta-\Delta\theta_1}^{\theta+\Delta\theta_1} \frac{\sigma}{4\pi} \, 2\pi \sin\theta \, d\theta = -\frac{\sigma}{2}\Big[\cos\theta\Big]_{\theta-\Delta\theta_1}^{\theta+\Delta\theta_1}$$

$$= -\frac{\sigma}{2}\Big[\cos(\theta+\Delta\theta_1) - \cos(\theta-\Delta\theta_1)\Big]$$

$$= -\frac{\sigma}{2}\Big[(\cos\theta\cos\Delta\theta_1 - \sin\theta\sin\Delta\theta_1) - (\cos\theta\cos\Delta\theta_1 + \sin\theta\sin\Delta\theta_1)\Big]$$

$$= \sigma \sin\theta \sin\Delta\theta_1$$

$$= \frac{\sigma(\sin\theta) r_D}{S_1}$$

Thus for spherically symmetrical scattering,

$$P_{CBA} = \frac{\exp\left[-N\sigma(S_1 + S_2)\right] r_D^{\,2}\sigma}{16\pi S_1^{\,2}(S_2+S_3)^2} \, .$$

Similarly

$$\int_{\theta-\Delta\theta_2}^{\theta+\Delta\theta_2} \sigma(\theta) \, 2\pi \sin\theta \, d\theta = \frac{\sigma(\sin\theta) \, r_D}{S_2 + S_3}$$

and

$$P_{ABC} = \frac{\exp\left[-N\sigma(S_1 + S_2)\right] r_D^{\,2}\sigma}{16\pi S_1^{\,2}(S_2+S_3)^2} \, .$$

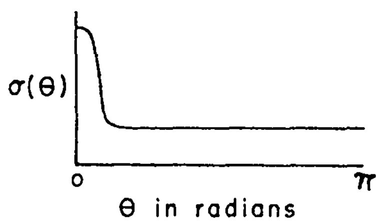
Therefore $P_{ABC} = P_{CBA}$ for spherically symmetrical scattering.

Since any atom in the sphere could have been chosen as the location of point B, we draw the conclusion that for spherically symmetrical scattering the same number of neutrons per second will be scattered into the detector in Case II as in Case I. We have already shown that the same number of neutrons per second are scattered out of the direct beam in Case II as in Case I. We have also shown that in Case I the number scattered in is equal to the number scattered out, except for the obliquity effect. Therefore in Case II, the number of neutrons per second scattered into the detector must be equal to the number of neutrons per second scattered out of the direct beam, except for the obliquity effect.

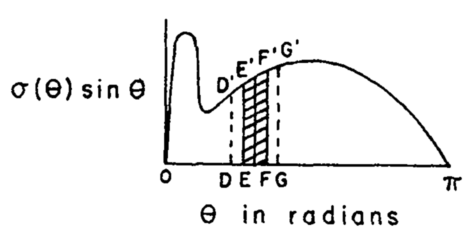
For the general case in which the scattering cross section is a function of angle $\sigma(\theta)$, we have for the ratio of the probabilities

$$\frac{P_{CBA}}{P_{ABC}} = \frac{S_1 \int_{\theta - \Delta\theta_1}^{\theta + \Delta\theta_1} \sigma(\theta) \sin\theta \, d\theta}{(S_2 + S_3) \int_{\theta - \Delta\theta_2}^{\theta + \Delta\theta_2} \sigma(\theta) \sin\theta \, d\theta}$$

For 14 Mev neutrons the differential cross section for elastic scattering is not known other than that it is largely in the forward direction. Let us arbitrarily choose an angular distribution such as



The product $\sigma(\theta) \sin\theta$ can then be represented as



The crosshatched area then represents the integral

$$\int_{\theta - \Delta\theta_2}^{\theta + \Delta\theta_2} \sigma(\theta) \sin \theta \, d\theta .$$

The width of this area for small $\Delta\theta_2$ is

$$2 \Delta \theta_2 \cong \frac{2 \cdot r_D}{S_2 + S_3} .$$

The area under the curve between the two dotted lines is

$$\int_{\theta - \Delta\theta_1}^{\theta + \Delta\theta_1} \sigma(\theta) \sin \theta \, d\theta ,$$

and its width for small $\Delta\theta_1$ is

$$2 \Delta \theta_1 \cong \frac{2 r_D}{S_1} .$$

The average ordinate of one of these areas is the area divided by the width

$$\frac{P_{CBA}}{P_{ABC}} = \frac{\dfrac{S_1}{2 r_D} \displaystyle\int_{\theta - \Delta\theta_1}^{\theta + \Delta\theta_1} \sigma(\theta) \sin \theta \, d\theta}{\dfrac{S_2 + S_3}{2 r_D} \displaystyle\int_{\theta - \Delta\theta_2}^{\theta + \Delta\theta_2} \sigma(\theta) \sin \theta \, d\theta}$$

$$\frac{P_{CBA}}{P_{ABC}} = \frac{\text{Av. ordinate of area D D' G' G}}{\text{Av. ordinate of area E E' F' F}}$$

This ratio approaches unity as $\Delta\theta_1$ and $\Delta\theta_2$ both become small or equal to each other. Also it should be noted that for some values of θ, P_{CBA}/P_{ABC} is greater than unity while for other values of θ, P_{CBA}/P_{ABC} is less than unity. When the average ordinates of the incremental areas are averaged over the entire range of θ the resultant average ordinate is the average ordinate of the entire area under the curve. This shows that the number of neutrons per unit time scattered into the detector is the same, when the scattering sphere is around the detector as when it is around the source.

There is still the error due to the obliquity effect which should be discussed. Consider the neutrons per cm^2 per second escaping from a spherical shell of radius, r, at whose center is a neutron source of strength, Q. This quantity may be written $Q/4\pi r^2$ or as $n_0 V_0$ where n_0 is the neutron density at the point in question and V_0 is the velocity of the neutrons which are traveling out radially from the source. Let a sphere of scattering material be placed around the source and assume only elastic scattering. The number of neutrons per second per cm^2 passing out of a spherical shell of radius, r, is still $Q/4\pi r^2$, but the velocities of the scattered neutrons are in general not radial. Since we have assumed elastic scattering from heavy nuclei, the speeds of the scattered neutrons are the same as before they were scattered. The term $Q/4\pi r^2$ may now be set equal to $n\overline{V}_r$ where n is the neutron density and $\overline{V}_r$ is the average radial velocity. Obviously $\overline{V}_r$ is less than V_0, although $\overline{V}_r$ approaches V_0 as the detector is moved farther from the source. Also $\overline{V}_r$ approaches V_0 for small angle scattering. Now

$$n_0 V_0 = Q/4\pi r^2 = n\,\overline{V}_r \quad .$$

If $\overline{V}_r$ is less than V_0, then n must be greater than n_0. Since the activity induced in a foil is proportional to nV regardless of the direction of V, the number of neutrons scattered into the detector would more than compensate for those scattered out.

Let us consider the possible magnitude of this effect. Suppose the distance from source, A, to detector, C, is three times the radius of the sphere as in Figure 2.

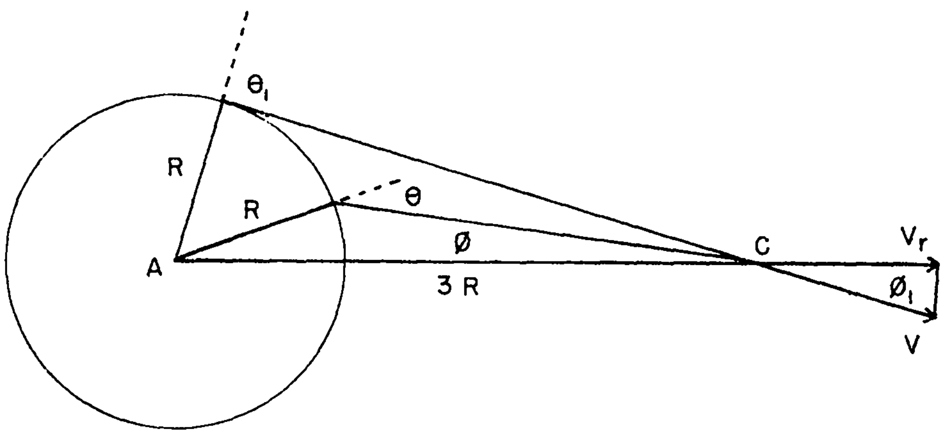


Figure 2

The minimum value that V_r can have is $V_r = V \cos \phi_1$ and this is for 90 degree scattering at the edge of the sphere.

$$\sin \phi_1 = 1/3$$

$$V_r = V \cos \phi = 0.943 \text{ V}$$

Even for isotropic scattering $\overline{V}_r$ would be of the order of 0.97 V. If scattering is mostly small angle, as is actually the case, even less error would be caused. For a scattering angle of 15 degrees at the edge of the sphere we have

$$\frac{\sin \phi}{R} = \frac{\sin (180^\circ - 15^\circ)}{3\ R}$$

$$\sin \phi = \frac{\sin 15^\circ}{3} = 0.08627$$

$$\sin \phi \qquad 0.9963$$

In this case the error is less than one-half per cent. These errors refer to the fraction of over-compensation and not to the per cent error caused in measuring an inelastic collision cross section.

The obliquity effect has just been discussed for Case I where the source is inside the sphere. However, it has already been shown that the number of neutrons scattered into the detector is the same for Case II as for Case I. Therefore the magnitude of the obliquity effect when the detector is in the sphere must depend upon the distance between source and detector and the radius of the sphere in the same way that it does when the source is in the sphere.

Experimental checks on the magnitudes of possible errors will be discussed later.

The inelastic collision cross sections were measured by the use of threshold detectors. What has been said about scattering out of the direct beam being compensated by neutrons scattered into the detector by the rest of the sphere holds also for inelastic scattering. However, if the detector is activated only by neutrons whose energy is greater than E_D, it will not count products of an inelastic collision whose energies are less than E_D. The three detectors used were copper, aluminum and phosphorus. The possible reactions, the thresholds when known, the half-lives of the reaction products, and the cross sections for the reaction at stated neutron energies are shown in Table I.

TABLE I

THRESHOLD DETECTOR INFORMATION

Reaction	Threshold	Half-life of Product	Cross Section at Specified Energy 1 barn = 10^{-24} cm^2	
$Cu^{63}(n,2n)Cu^{62}$	11.5±.5 Mev[1]	9.9±.1 min	0.32±.08 barn	14 Mev
$Cu^{65}(n,2n)Cu^{64}$	--	12.8 hrs[2]	--	--
$Cu^{63}(n,\gamma)Cu^{64}$	exothermic	12.8 hrs[2]	2.0±.4 barns[2]	thermal
$Cu^{65}(n,\gamma)Cu^{66}$	exothermic	5.0 min[2]	0.56±.11 barn[2]	thermal
$Al^{27}(n,p)Mg^{27}$	~2.5 Mev[3]	9.6±.1 min[4]	~0.03 barn[3]	14 Mev
$Al^{27}(n,\alpha)Na^{24}$	~3 Mev	14.8 hrs[5]	--	- -
$Al^{27}(n,\gamma)Al^{28}$	exothermic	2.30±.03 min[4]	0.21±.04 barn[2]	thermal
$Al^{27}(n,2n)Al^{26}$	- -	7.0 sec[6]	- -	- -
$P^{31}(n,p)Si^{31}$	1.40±.05 Mev[7]	160±10 min	~0.06 barn[7]	3 Mev
$P^{31}(n,\alpha)Al^{28}$	~2.5 to 3 Mev[7]	2.3 min[4]	- -	- -
$P^{31}(n,\gamma)P^{32}$	exothermic	14.3 da[2]	0.23±.05 barn[2]	thermal
$P^{31}(n,2n)P^{30}$	- -	2.55 min[8]	- -	- -

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With a copper detector, the reaction used was $Cu^{63}(n,2n)Cu^{62}$. The half-life was measured and found to be 9.9 ± .1 minutes. The threshold for this reaction is about 11.5 ± .5 Mev and the cross section at 14 Mev is 0.33 ± .08 barn. The $Cu^{65}(n,2n)Cu^{64}$ reaction also takes place but the half-life of the product is 12.8 hours. When foils were irradiated for only ten or fifteen minutes the amount of long life activity was negligible compared to the short life activity. Both stable copper isotopes have appreciable cross sections for thermal neutron capture as is shown in Table I. As has already been said, short irradiations were used and the amount of 12.8-hour activity was negligible. Several attempts were made to detect a five-minute activity, but none could be detected. Cadmium shielding around the foils produced no change in the observed half-life.

Four reactions are possible with aluminum detectors. The (n,2n) reaction leads to Al^{26} whose half-life is only seven seconds. This activity was not detected since there was always a waiting time of from three to five minutes between the end of irradiation and the beginning of counting. The (n,γ) reaction as with copper foils was not detected. The $Al^{27}(n,\alpha)Na^{24}$ reaction was produced but since the half-life of Na^{24} is 14.8 hours and irradiations were for not more than twenty minutes, this activity was found to be negligible also. The reaction which was used was $Al^{27}(n,p)Mg^{27}$ with a threshold of about 2.5 Mev and a cross section for 14 Mev neutrons of about 0.03 barn. The half-life of Mg^{27} is 9.6 ± .1 minutes.

The third threshold detector used was phosphorus. Polythene was impregnated with red phosphorus and used in the form of strips one-half inch wide and about five-thousandths of an inch thick. These strips were 49.5 percent phosphorus by weight, and were prepared by Mr. James S. Church of CMR-6. Again, as with the other detectors, no activity due to neutron capture was observed. An activity with a half-life of two or three minutes was observed which could have been due to either the (n,2n) reaction or the (n,α) reaction or to both. The reaction which was used was $P^{31}(n,p)Si^{31}$ with a threshold at 1.40 $\pm$ .05 Mev and a cross section of about 0.06 barn at 3 Mev. The half-life obtained by us was 160 $\pm$ 10 minutes. Irradiation times varied from eighty minutes to two hours. Twenty minutes' waiting time was used so that the short life activity would die out before starting to count the longer life activity.

CHAPTER III

NEUTRON SOURCE

The high energy neutrons were obtained by bombarding a thick tritium target with 220 kev deuterons. The nuclear reaction can be conveniently written as

$$_1H^3 + {}_1H^2 \rightarrow {}_0n^1 + {}_2He^4 + Q,$$

where Q represents the energy liberated and is about 17 Mev in this case. The target consisted of a tungsten disc to which was fused a zirconium foil. The tritium was absorbed in the zirconium[9].

The accelerating potential was furnished by a 55 kilovolt transformer and a Cockcroft-Walton voltage quadrupling circuit[10,11]. A Zinn type ion source[12,13] was used, the deuterium being admitted by means of a paladium valve. In general, an ion source will furnish both atomic and molecular ions and since there will usually be some hydrogen present in the deuterium, ions such as H^+, D^+, H_2^+, HD^+, D_2^+ will be formed. If the deuterium is reasonably pure, the ions will be mainly D^+ and D_2^+ corresponding to atomic masses two and four. In general from this source the molecular beam is found to be four or five times as intense

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9) E. R. Graves, A. A. Rodrigues, M. Golblatt and D. I. Meyer, R. S. I. (to be published)(1949).

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12) W. H. Zinn, Phys. Rev. 52, 655 (1937).

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as the atomic beam. The limiting factor for a strong neutron source is the power dissipation at the target. For a given current the molecular beam consists effectively of twice as many deuterons, each having only half the energy of those deuterons in the atomic beam. If the thick target yield in neutrons per deuteron were greater than one-half as much for 110 kev as it is for 220 kev, then one should use the molecular beam since this would cause a negligible decrease in neutron energy while increasing the yield in neutrons per watt. Actually 220 kev deuterons give more than twice the thick target yield of 110 kev deuterons. Therefore the atomic beam is more desirable when the beam intensity is limited by the rate at which heat can be dissipated at the target. The separation of atomic and molecular beams was accomplished by passing the fast moving ions between the poles of an electromagnet, the atomic beam being deflected more than the molecular beam. Water cooling is used to dissipate the heat where the molecular beam strikes the side of the tube.

At the target, a side tube goes to a proportional counter which counts the alpha particles formed by the same reaction which produces the neutrons. In this way the intensity of the neutron source can be continuously monitored.

The neutrons from this source have very little energy spread. By the use of collision mechanics it can be shown that in the forward direction the neutron energies lie between 13.9 Mev and 15.0 Mev, while in the backward direction the energy spread is from 13.0 Mev to 13.9 Mev. In any direction perpendicular to the deuteron beam, the total spread in neutron energy is only about 0.1 Mev. The primary energy of these 90 degree neutrons was calculated to be $13.95 \pm .05$ Mev. The $\pm$ 0.05 Mev refers to the energy spread and not to the absolute accuracy of the 13.95 Mev.

The energy spectrum of this source has been measured using photographic plates[14]. The peak occurs at about 14 Mev,and has a total spread at half maximum of about 0.5 Mev. The method used depends upon recoil protons, and the observed energy spread can be accounted for entirely by straggling terms introduced by the method of measurement. In other words, a monoenergetic source of 14 Mev neutrons would give the same number versus energy curve as was observed.

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14) E. R. Graves and L. Rosen,Phys. Rev. (to be published)(1949).

CHAPTER IV

EXPERIMENTAL CHECKS ON METHOD

Inelastic collison cross sections were measure in the following way. If the number of neutrons scattered into the detector compensates for those scattered out of the direct beam, then any decrease in neutron intensity must be due to removal of high energy neutrons by inelastic collision. Let the neutron intensity at the detector be I when the scattering sphere is present either around the source or around the detector and I_o at the same place when the sphere is removed. Then we define the transmission as

$$T = I/I_o,$$

and since

$$I = I_o \exp(-N\sigma r),$$

we get an expression for the cross section,

$$\sigma = \frac{-\ln T}{Nr},$$

where N is the number of scattering atoms per unit volume and r is the thickness of scattering material. N can be calculated from Avogadro's number, the atomic weight and density of the scatterer. The transmission is determined as follows. The saturated activity of a detector foil A_D is defined as the activity which it would have if left in a neutron flux for an infinitely long time. For a particular foil, the saturated activity is directly proportional to the neutron intensity,

$$A_D = k\,I.$$

If a particular foil is irradiated for a time t_i and is then counted for a time t_c after a time t_w has elapsed between the end of irradiation and the start of counting, the saturated activity may be calculated from the relation

$$A_D = \frac{C_D \lambda \exp(\lambda t_w)}{\epsilon \left[1-\exp(-\lambda t_i)\right] \left[1-\exp(-\lambda t_c)\right]}$$

where C_D is the number of counts observed, λ is the decay constant, and ϵ is the counting efficiency. The transmission can then be calculated from

$$T = I/I_o = \frac{(A_D)_{in}}{(A_D)_{out}} ,$$

where the subscripts "in" and "out" refer to the presence or absence of the scattering sphere. In practice it is not feasible to keep the neutron intensity constant from one run to the next. In the case where the source remains outside the sphere a monitor foil of the same material as the detector foil is placed in some position where it will receive a negligible number of scattered neutrons from the sphere. Without the sphere in place, the ratio of the neutron intensity at the detector foil to the neutron intensity at the monitor foil is a constant,

$$(I_D/I_M)_{out} = k_1 ,$$

and

$$k_1 = (A_D/A_M)_{out} .$$

If in addition to being irradiated simultaneously, the detector and monitor foils are counted simultaneously on two different counters,

$$k_1 = (\epsilon_M/\epsilon_D)\ (C_D/C_M)_{out}.$$

When the sphere is placed around the detector foil the ratio of its activity to the monitor activity is reduced by another factor which is the transmission,

$$(A_D/A_M)_{in} = k_1\ T.$$

Again, if irradiation time, waiting time and counting time are identical we have

$$k_1\ T = (\epsilon_M/\epsilon_D)\ (C_D/C_M)_{in}\ .$$

Therefore

$$T = \frac{k_1\ T}{k_1} = \frac{(\epsilon_M/\epsilon_D)(C_D/C_M)_{in}}{(\epsilon_M/\epsilon_D)(C_D/C_M)_{out}}\ ,$$

or

$$T = \frac{(C_D/C_M)_{in}}{(C_D/C_M)_{out}}\ ,$$

which is not dependent upon a knowledge of the half-life. This relation holds only if both detector foils and both monitor foils are matched as to size, shape and weight. Actually the foils were cut as nearly as possible to the same size and shape. They were then weighed accurately on a chemical balance. In making the calculations, the number of counts was divided by the mass of the foil so as to correct for small variations in weight.

The equivalence of interchanging source and detector was checked experimentally. When the sphere was placed around the source it was no longer possible to use a monitor foil. The neutron flux was then monitored by means of the alpha counter. The deuteron beam was held as nearly constant as possible and the alpha count was recorded every minute. The irradiation time, waiting time and counting time were made the same for all runs. The alpha counts per minute were then weighted by the factor $\exp(-\lambda t)$ where t is the remaining irradiation time. This gives the latter part of the irradiation a greater weight than the early part. It was found, however, that in general there was less than one-half percent difference between weighted average and unweighted average. The transmission was then calculated from the equation,

$$T = \frac{(C_D/m\alpha)_{in}}{(C_D/m\alpha)_{out}} ,$$

where m is the mass of the foil and α is the weighted alpha count per minute. The subscripts "in" and "out" refer to the presence or absence of the sphere around the source. The accuracy of this method was checked by using it in addition to a monitor foil, when the sphere was around the detector.

Two spheres were constructed to fit around the source. One sphere was made of graphite and the other was made of wrought aluminum alloy 24S. The latter contained 93.4 percent aluminum, 4.5 percent copper, 0.6 percent manganese and 1.5 percent magnesium. In order to fit around the source, the spheres had to be made in three pieces, one hemisphere and two half-hemispheres. Four holes led into the sphere, one each for the target support, deuteron beam, alpha monitor, and side pumping lead. The first three holes accommodated 3/4-inch brass tubes, the fourth hole was not a uniform cylinder because it contained a slightly curved copper tube and a joint. This hole averaged slightly more than one inch in diameter. The aluminum sphere had one additional radial one-inch hole. All holes were fitted with removable plugs.

In the case of the graphite sphere the holes comprised about three per cent of the total volume. To check the effects of these holes, irradiations were performed successively with no sphere, detector in sphere without plugs in holes, and detector in sphere having plugs in holes. The sphere was oriented in such a way that the holes would have the greatest effect if scattering were mainly small angle. The transmission as measured with plugs was $0.606 \pm .006$ and without plugs $0.594 \pm .006$. This is a difference of (2 ± 2) per cent, showing that the effect of the holes is not serious, being hardly detectable. When this same graphite sphere was placed around the source, the transmission was found to be $0.613 \pm .007$. When the detector was in the aluminum sphere and the holes were plugged, the transmission was $0.584 \pm .007$, and when this sphere was around the source the transmission was $0.601 \pm .008$. The source is known to be slightly non-symmetric with respect to both energy and yield. Therefore the only conclusion which can be drawn from these results is that any error introduced by interchanging source and detector must be less than two or three per cent.

Checks were made on the effects of distance both with an aluminum detector in bismuth sphere and with a copper detector in an iron sphere. In the former case, the sphere containing the detector was moved from a distance of approximately three times its radius to a point about five times its radius from the source. At the near point the transmission was 0.765 $\pm$ .012, while at the far point the transmission was 0.761 $\pm$.015, which is the same within experimental error. The iron sphere was moved from a distance of about twice its radius to a distance of about four and one-half times its radius from the source. At the near point the transmission was 0.535 $\pm$.006 and at the far point it was 0.541 $\pm$. 008, which again shows no effect within experimental error.

In checking the effect of shell thickness, the cross sections were calculated from the transmissions obtained with spheres of different thickness. The ratio of the per cent uncertainty in cross section to the per cent uncertainty in transmission is greater than unity for all transmissions observed in these experiments. This ratio varies inversely as ln T, approaching infinity as the transmission approaches unity. For a transmission of 0.60 the uncertainty in cross section is about twice the uncertainty in T.

With the bismuth sphere and a copper detector, a cross section of 2.53 $\pm$ .07 barns (1 barn = 10^{-24} cm^2) was obtained for a shell thickness of 4.22 cm and 2.58 $\pm$.06 barns was obtained for a shell 5.72 cm thick. Aluminum detectors in the two thicknesses of bismuth gave similar results (see Table II). With copper detectors in iron shells of thicknesses 5.02 cm, 6.24 cm, and 6.82 cm the following cross sections were obtained: 1.47 $\pm$.03 barns, 1.46 $\pm$ .12 barns, and 1.45 $\pm$ .02 barns.

TABLE II

EFFECTS OF SOURCE DISTANCE AND SHELL THICKNESS

ON MEASURED CROSS SECTIONS

Sphere	Detector	Distance Source to Detector cm	Sphere Radius cm	Sphere Thickness cm	Transmission T	σ barns	Av. σ barns
Bi	Cu	16.6	5.5	4.22	0.740 ± .006	2.53±.07	2.56±.05
Bi	Cu	16.6	7.0	5.72	0.660 ± .006	2.58±.06	
Bi	Al	16.6	5.5	4.22	0.765 ± .012	2.25±.13	2.28±.08
Bi	Al	16.6	7.0	5.72	0.689 ± .012	2.31±.11	
Bi	Al	27.4	5.5	4.22	0.761 ± .015	2.30±.15	
Fe	Cu	16.6	7.62	6.82	0.4315 ±.005	1.45±.02	1.45±.02
Fe	Cu	16.6	7.62	6.24	0.463 ± .029	1.46±.12	
Fe	Cu	15.0	7.62	5.02	0.535 ± .006	1.47±.03	
Fe	Cu	35.5	7.62	5.02	0.541 ± .008	1.44±.04	
Fe	Al	15.0	7.62	5.02	0.595 ± .007	1.22±.03	1.21±.03
Fe	Al	16.6	7.62	6.24	0.539 ± .013	1.17±.05	

CHAPTER V

REDUCTION OF DATA AND EXPERIMENTAL RESULTS

The general procedure for taking data has already been discussed in connection with the description of the experimental checks on the method. There was also some discussion of procedure in connection with the description of the characteristics of the various detector foils.

At first it was thought that it would not be necessary to irradiate as many foils without scattering spheres as with. This was because by keeping the same positions for detector and monitor foils the quantity $(C_D/C_M)_{out}$ should remain the same regardless of which scattering spheres were used for determining the various values of $(C_D/C_M)_{in}$. It was finally decided, however, that better results were obtained when irradiations with and without the sphere were alternated. The positions of the foils relative to the target tube could be kept constant to within better than $\pm$ 0.1 cm. However, the position of the neutron source was determined by the intersection of the deuteron beam with the target. This point of intersection could not be determined exactly, although the deuteron beam was limited by diaphragms to a region of circular cross section of about 0.24 cm radius. The focused beam at the target might have an appreciably smaller radius. The position of the beam spot on the target can be moved around within the above limits by varying the electric and magnetic deflecting fields. The greatest neutron yield does not always come from the center of the target. As a constant deuteron beam is moved about the face of the target, the alpha count shows that there are spots on the target which give higher neutron yields than other spots[9]. In the earlier irradiations it is probable that the deuteron beam was positioned for maximum neutron yield. Later on, care was taken to keep the deutron beam centered with respect to the limiting diaphragms. This was done by first increasing the magnetic field current until the deuteron current to the target began to decrease rapidly due to its being partially intercepted by one edge of a diaphragm. The magnetic field current would then be decreased until the beam was partially blocked by the other side of the diaphragm. The field current was then set at a value half-way between the two limits just mentioned. The same procedure was used with the electric field for locating the beam in an east-west plane.

The copper and aluminum foils were strips about 12 inches long and 3/8 inch wide with tapered ends so that they could be wound in the form of a helix and fitted into a cylindrical brass foil holder about 1.5 inch long and 1 inch in diameter which could then be placed on a Geiger tube in a reproducible geometry for counting. Foils of different thickness were tried but the best results were obtained with copper foils (0.0030 $\pm$.0005) inch thick and with aluminum foils(0.008 $\pm$ .001) inch thick. The foils were rolled up in tight spirals for irradiation.

Counting was done in a counting room which was designed and set up during the war by Alvin C. Graves, Robert L. Walker and Roland W. Davis. The background was quite constant at about 24 counts per minute. Initial counting rates with copper and aluminum foils were of the order of 1,000 to 2,000 counts per minute with total counts per foil running from about 10,000 to 20,000. Precaution was taken not to allow the counting rates for detector and monitor foils to become radically different at high counting rates. This was to guard against counting losses becoming appreciably greater on one counter than on the other. As a check on this later effect the ratio (C_D/C_M) was determined for different counting rates as the activity died away. No consistent or significant difference could be detected.

The phosphorus in polythene foils were also cut in strips of approximately the same size as the copper and aluminum foils but they presented other difficulties. For one thing the foils were not of uniform thickness. The initial activity after two hours' bombardment was only four to six times the normal background for these foils. In add ition to this each foil apparently had a small amount of very long life activity due perhaps to some impurity. A particular foil had a constant background, but different foils had backgrounds ranging from about 33 counts per minute to about 55 counts per minute. The normal tube background was about 24 counts per minute.

At first it seemed impossible to obtain consistent results with phosphorus foils even though corrections for mass differences were applied.

Evidently the phosphorus was not uniformly distributed throughout all of the foils, although the variation in thickness was probably responsible for some of the inconsistencies. Consistent results were finally obtained by using the same pair of foils for measuring $(C_D/C_M)_{in}$ as was used for measuring $(C_D/C_M)_{out}$. Both measurements could not be performed on the same day, since it was necessary to allow time for 160 minute half-life activity to die out.

In general only three pairs of foils could be irradiated and counted in one day. For example, pairs one and three would be irradiated with the detector foil in the sphere and pair number two would be irradiated with the detector foil in the open on one day. The next day foil pairs one and three would be irradiated in the open and pair number two would be irradiated with the detector foil inside of a sphere.

Irradiation times and counting times were of the order of two hours each, separated by a waiting time of twenty minutes. This waiting time was made necessary by the presence of a two or three minute half-life as mentioned in the section on threshold detectors.

The data and results obtained by using the three threshold detectors in spheres of various elements are shown in the following tables. The headings of the various columns are defined as follows:

Element = Element of which the scattering sphere was constructed and whose inelastic collision cross section is being measured.

S_D = Distance of detector foil from source.

S_M = Distance of monitor foil from source.

r = Sphere thickness

T = Transmission.

σ = Inelastic collision cross section in barns.

1 barn = 10^{-24} cm^2.

TABLE III

DATA AND RESULTS USING COPPER DETECTOR

Element	S_D	S_M	r	(C_D/C_M)out	(C_D/C_M)in	T	σ
	cm	cm	cm				barns
Be	20.5	22.8	3.40	1.116	0.807		
				1.117	0.813		
				1.210	0.869		
				1.215	0.865		
				1.164	0.891		
				1.160	0.854		
				1.165	0.848		
				1.163±.010	0.848±.008	0.729±.008	0.82±.03
B	20.5	22.0	4.05	1.029	0.875		
				1.030	0.833		
				1.017	0.826		
				1.021	0.868		
				1.041	0.886		
				1.038	0.870	0.831 (uncorrected for	
				1.035	0.848	Cu shell) after	
					0.841	correction	
				1.030±.005	0.856±.015	0.836±.015	0.69±.10
C	20.5	21.9	8.10	1.089	0.666		
				1.089	0.695		
				1.119	0.669		
				1.087	0.666		
				1.107	0.677		
				1.129	0.658		
					0.676		
				1.103±.009	0.672±.005	0.609±.008	
				alpha-monitored	(see text)		
				9.48	5.79		
				9.30	5.83		
				9.62	5.62		
				9.33	5.62		
				9.30	5.67		
				9.37	5.53		
					5.72		
				9.40±0.07	5.68± .05	0.604±.008	
						0.606±.006	0.85±.02

TABLE III (continued)

Element	S_D cm	S_M cm	r cm	$(C_D/C_M)_{out}$	$(C_D/C_M)_{in}$	T	σ barns
Al	16.6	15.05	5.23	0.778	0.577		
				0.775	0.583		
				0.819	0.568		
				0.791±.015	0.576±.006	0.728±.016	

Foil holders, clamps, rods, etc. were removed for another experiment and then were replaced for the following data.

Element	S_D cm	S_M cm	r cm	$(C_D/C_M)_{out}$	$(C_D/C_M)_{in}$	T	σ barns
	16.6	15.05	5.23	0.745	0.537		
				0.749	0.533		
					0.543		
				0.747±.010	0.538±.005	0.720±.012	
						0.724±.010	1.06±.05
Fe	16.6	15.05	6.82	0.732	0.315		
				0.730	0.319		
				0.733	0.316		
					0.313		
				0.732±.004	0.316±.003	0.431±.005	1.45±.02
	16.6	15.05	6.24	0.787	0.395		
				0.764	0.376		
				0.832	0.341		
				0.832	0.395		
					0.391		
				0.804±.027	0.372±.020	0.463±.029	1.46±.12
	15.0	18.0	5.02	1.42	0.758		
				1.39	0.752		
				1.42	0.749		
				1.40			
				1.41±.01	0.753±.005	0.535±.006	1.47±.03
	35.5	25.1	5.02	0.483	0.263		
				0.495	0.270		
				0.495	0.266		
					0.263		
				0.491±.005	0.265±.003	0.540±.008	1.44±.04

TABLE III (continued)

Element	S_D	S_M	r	$(C_D/C_M)_{out}$	$(C_D/C_M)_{in}$	T	σ
	cm	cm	cm				barns
Cd	16.6	15.05	5.85	0.765	0.476		
				0.747	0.469		
				0.778	0.455		
				0.775	0.466		
				0.819	0.451		
					0.467		
					0.472		
				0.775±.010	0.465±.005	0.600±.010	1.89±.0
Au	20.5	22.8	3.40	1.172	0.702		
				1.154	0.696		
				1.141	foil fell		
				1.151	0.704		
				1.153	0.722		
				1.131	0.681		
				1.137	0.700		
				1.150	0.686		
				1.149±.005	0.699±.005	0.608±.005	2.51±.04
Pb	20.5	22.8	5.71	1.148	0.688		
				1.144	0.708		
					0.728		
				1.148	0.730		
				1.171	0.741		
				1.166	0.727		
				1.128	0.700		
				1.148	0.704		
					0.680		
				1.160	0.704		
				1.150±.005	0.711±.007	0.618±.006	2.56±.06
Bi	16.6	15.05	4.22	0.790	0.583		
					0.603		
				0.800	0.589		
					0.600		
				0.807	0.594±.006	0.740±.007	2.53±.07
			5.72	0.807	0.525		
					0.525		
				0.810	0.533		
					0.559		
				0.799	0.527		
				0.802±.003	0.529±.005	0.660±.006	2.58±.06

TABLE IV

DATA AND RESULTS USING ALUMINUM DETECTOR

Element	S_D	S_M	r	$(C_D/C_M)_{out}$	$(C_D/C_M)_{in}$	T	σ
	cm	cm	cm				barns
Be	20.5	21.9	3.40	1.258	1.192		
				1.285	1.250		
				1.287	1.163		
				1.277±.010	1.202±.030	0.94±.03	$0.16^{+.06}_{-.08}$
B	21.0	22.0	4.05	1.118	1.033		
				1.120	1.054		
				1.129	1.054	0.935	(uncorrected
				1.118	1.054		for copper
				1.136	1.059		shell)correcte
				1.124±.005	1.051±.005	0.939±.007	0.24±.04
Al	16.6	15.05	5.23		0.643		
				0.785	0.629		
					0.622		
				0.737	0.629		
					0.631		
				0.771	0.644		
				0.764±.015	0.633±.006	0.828±.018	0.62±.07
Fe	16.6	15.05	6.24		0.413		
				0.776	0.415		
				0.745	0.417		
				0.774	0.408		
				0.762	0.409		
				0.764±.015	0.412±.004	0.539±.012	1.17±.05
	15.0	10.0	5.02	0.446	0.2646		
				0.447	0.2637		
				0.440	0.2647		
				0.444±.004	0.264±.002	0.595±.007	1.22±.03
Cd	16.6	15.05	5.85		0.484		
				0.782	0.475		
					0.488		
				0.760	0.493		
					0.495		
				0.737	0.479		
				0.760±.010	0.486±.007	0.639±.012	1.66±.07

TABLE IV (continued)

Element	S_D cm	S_M cm	r cm	$(C_D/C_M)_{out}$	$(C_D/C_M)_{in}$	T	σ barns
Au	20.5	22.8	3.40	1.186	0.817		
				1.190	0.793		
				1.201	0.778		
				1.229	0.813		
				1.169	0.800		
				1.201	0.818		
				1.234	0.804		
				1.219	0.785		
				1.204±.015	0.801±.012	0.665±.012	2.06±.09
Pb	20.5	22.8	5.71	1.240	0.826		
				1.254	0.818		
				1.252	0.812		
				1.242	0.800		
				1.230	0.798		
				1.242	0.805		
				1.248	0.815		
				1.244±.006	0.811±.005	0.651±.004	2.29±.04
Bi	16.6	15.05	4.22		0.608		
				0.810	0.621		
					0.576		
					0.603		
				0.776	0.618		
					0.608		
					0.612		
				0.784	0.607±.006	0.765±.012	2.25±.13
	16.6	15.05	5.72		0.551		
				0.801	0.541		
				0.793±.010	0.546±.007	0.689±.012	2.31±.11
	27.4	15.05	4.22		0.223		
				0.302	0.219		
					0.227		
				0.285	0.224		
				0.293±.004	0.223±.003	0.761±.015	2.30±.15

TABLE V

DATA AND RESULTS USING PHOSPHORUS DETECTOR

$S_D = 15.0$ cm; $S_M = 10.0$ cm

Element	Detector Foil No.	Monitor Foil No.	r cm	$(C_D/C_M)_{out}$	$(C_D/C_M)_{in}$	T
Fe	4	1	5.02	0.496	0.358	0.722
Cd	4	1	5.22	0.494	0.381	0.768
Au	4	1	3.40	0.495	0.375	0.756
Au	4	1		0.500	0.362	0.730
Pb	4	1	5.71	0.496±.003	0.422	0.851
Bi	4	1	5.72		0.410	0.827
Bi	4	1			0.431	0.869
Fe	5	2	5.02	0.461	0.336	0.723
Cd	5	2	5.22	0.474	0.353	0.759
Au	5	2	3.40	0.460	0.353	0.759
Pb	5	2	5.71	0.480	0.391	0.841
Bi	5	2	5.72	0.470	0.404	0.869
				0.442		
				0.465±.005		
Fe	6	7	5.02	0.507	0.363	0.702
Cd	6	7	5.22	0.524	0.389	0.752
Au	6	7	3.40	0.501	0.385	0.745
Pb	6	7	5.71	0.542	0.435	0.841
Bi	6	7	5.72	0.510	0.427	0.826
				0.517±.010		

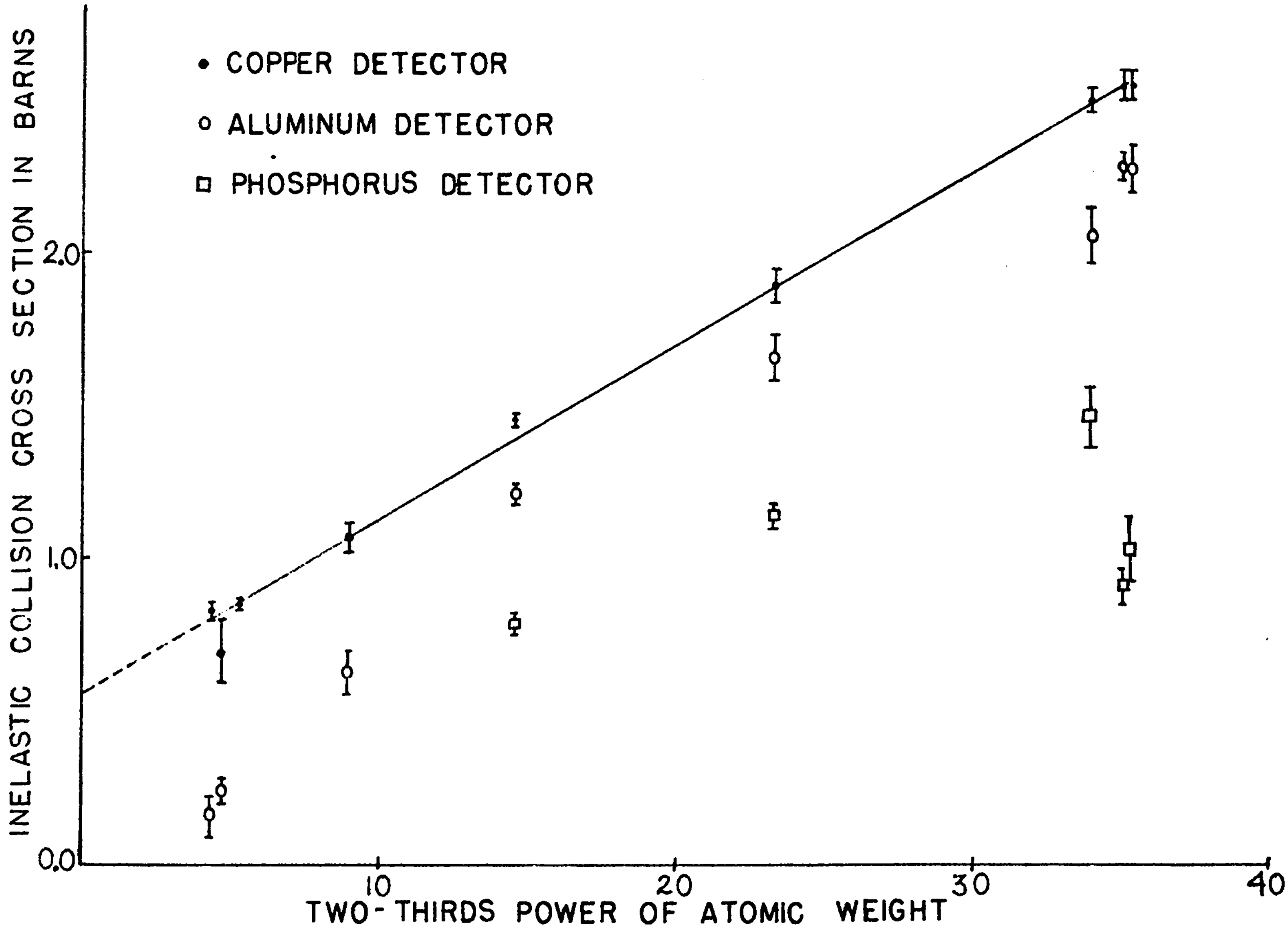
Element	r cm	Av. T	σ barns
Fe	5.02	0.716±.007	0.78±.03
Cd	5.22	0.760±.007	1.14±.04
Au	3.40	0.748±.015	1.47±.10
Pb	5.71	0.844±.010	0.91±.06
Bi	5.72	0.848±.015	1.03±.11

TABLE VI

SUMMARY OF RESULTS

Element	A Atomic Weight	$A^{2/3}$	Density gm/cc	N Atoms per cc $\times 10^{-24}$	Cross Section in Barns ($E_1 = 14$ MeV) $E_2 < 11.5$ MeV Cu Detector	< 2.5 MeV Al Detector	< 1.4 MeV P Detector
Be	9.02	4.33	1.70 ± .01	0.1140 ± .0010	0.82 ± .03	0.16 (+.06 or -.08)	
B*	10.20	4.70	1.08 ± .06	0.0640 ± .0050	0.69 ± .10	0.24 ± .04	
C	12.01	5.24	1.45 ± .01	0.0726 ± .0002	0.85 ± .02		
Al	26.97	8.99	2.61 ± .02	0.0583 ± .0005	1.06 ± .05	0.62 ± .07	
Fe	55.85	14.61	7.88 ± .04	0.0848 ± .0005	1.45 ± .02	1.21 ± .03	0.78 ± .03
Cd	112.41	23.28	8.61 ± .05	0.0461 ± .0003	1.89 ± .06	1.66 ± .07	1.14 ± .04
Au	197.2	33.88	19.1 ± .2	0.0583 ± .0006	2.51 ± .04	2.06 ± .09	1.47 ± .10
Pb	207.2	35.02	11.3 ± .1	0.0328 ± .0003	2.56 ± .05 0.27	2.29 ± .04 1.38	0.91 ± .06 0.31
Bi	209.0	35.22	9.74 ± .08	0.0281 ± .0003	2.56 ± .05	2.28 ± .08	1.03 ± .11

*82 percent B^{10}, 18 percent B^{11}.



COPPER DETECTOR
ALUMINUM DETECTOR
PHOSPHORUS DETECTOR
INELASTIC COLLISION CROSS SECTION IN BARNS
0.0
1.0
2.0
10
20
30
40
TWO-THIRDS POWER OF ATOMIC WEIGHT

The results with copper detectors indicate a linear relation between the inelastic collision cross section and the two-thirds power of the atomic weight. The positive intercept on the cross section axis at atomic weight zero is in agreement with other investigations [15, 16] and has been explained in terms of the cross section of the bombarding neutrons and a small finite range for nuclear forces which is independent of the size of the nucleus [15, 16]. The cross section values for the lighter elements herein reported may be somewhat high due to the inclusion of some elastic scattering. A neutron of initial energy, E_o, elastically scattered through a laboratory angle, θ, by a nucleus of mass, A, will have after being scattered an energy, E, given by

$$E = E_o \, (A^2 + 2A \cos \theta + 1)/(A + 1)^2.$$

If a nuetron after an elastic collision does not have enough energy to activate the detector, it will in effect be measured as an inelastic collision. A nuetron elastically scattered through an angle of zero degrees suffers no loss of energy. The minimum energy after an elastic collision is for a scattering angle of 180 degrees. If a neutron whose initial energy is 14 Mev collides with an aluminum nucleus, the minimum energy that the neutron can have after collision is 12.1 Mev. This is still above the threshold of the copper

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15) R. Sherr, Phys. Rev. 68, 240 (1945).

16) E. Amaldi and B. N. Cacciapuoti, Phys. Rev. 71, 739 (1947).

detector, although the cross section for the $Cu^{63}(n,2n)Cu^{62}$ reaction is lower at this energy. For beryllium, which was the lightest element used, all neutrons elastically scattered through angles greater than 90 degrees will have energies below the threshold of the copper detector. Let us assume spherically symmetric elastic scattering, so that the neutrons elastically scattered out of the direct beam are only one-half compensated by those scattered into the detector. If elastic and inelastic cross sections, σ_e and σ_i, are equal then the corrected value of σ_i for beryllium should be about 0.57 barn instead of 0.82 barn. If forward scattering predominates, the error would of course be less. In any case, we could not be obtainining a value greater than the total cross section.

The total cross sections of the lighter elements measured by Cook et al.[17)] for 90 Mev neutrons are considerably smaller than our inelastic collision cross sections for 14 Mev neutrons. For the heaviest elements, their total cross sections are nearly twice as large as our inelastic collision cross sections. Serber[18)] explains these very low cross sections of the lighter elements as being due to a transparency effect for very high energy neutrons. He says that for very high energy neutrons (100 Mev) one would expect a total cross section still close to twice the geometric cross section for the heaviest elements, but for light elements the cross section should drop considerably below this value.

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17) L. J. Cook, E. M. McMillan, J. M. Peterson, and D. C. Sewell, Phys. Rev. 75 , 7 (1949).

18) R. Serber, Phys. Rev. 72, 1114 (1947).

For inelastic scattering or (n,n) reactions, theoretical considerations[19] indicate that the energy distribution of the scattered neutrons is such as to make the most probable energy well below the energy of the incident neutron. This type of distribution is at least consistent with the results obtained by us for the heavier elements with various threshold detectors. There is less than 25 percent difference between the cross sections obtained with copper detectors and those obtained with aluminum detectors, although the respective thresholds are 11.5 Mev and 2.5 Mev. This indicates that if a scattered neutron has an energy less than 11.5 Mev, the probability is quite high that its energy is also less than 2.5 Mev. The cross sections measured with phosphorus detectors (threshold 1.4 Mev) show a considerable drop below the cross sections measured with aluminum detectors. This indicates that a good many of the inelastically scattered neutrons have energies lying between 1.4 Mev and 2.5 Mev.

The energy distribution of the scattered neutrons depends upon the level spacings of the compound nucleus and should not be expected to be the same for various elements. From the results obtained here, it would seem that a considerably larger fraction of the neutrons scattered from lead and bismuth have energies between 1.4 Mev and 2.5 Mev than do those neutrons scattered from gold.

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19) V. F. Weisskopf and D. H. Ewing, Phys. Rev. 57, 472 (1940).

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