THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 60, NO. 10 NOVEMBER 15, 1941 SECOND SERIES

The Scattering of Fast Neutrons by Lead

HENRY F. DUNLAP* AND ROBERT N. LITTLE
Rice Institute, Houston, Texas

(Received July 10, 1941)

The scattering of D-D neutrons by lead has been investigated with a cloud chamber. The energy distribution of the inelastically scattered neutrons has been determined from 0.6 to 2.0 Mev, and it has been found that the distribution does not agree with the theoretical predictions of Weisskopf, and of Weisskopf and Ewing. The cross section for inelastic scattering has been determined, and is $1.31\pm0.53\times10^{-24}$ cm^2. It has been shown that elastic scattering is not spherically symmetric, and is very small for angles greater than about 50°.

It has been known for several years that many elements emit gamma-rays when they are bombarded by fast neutrons, and it has been shown that, at least in some cases, these are due to the inelastic scattering of the neutrons as they traverse the scatterer.[1–5] The cross section for this gamma-ray production has been obtained by Lea, by Gibson, Grahame, and Seaborg, by Kikuchi, Aoki, and Husimi, and by Nonaka.[1,2,4,5] The first two experiments were performed with the nonhomogeneous neutrons from the Ra-Be reaction, while Kikuchi and collaborators, and Nonaka, have used the more nearly homogeneous neutrons from the deuteron-deuteron reaction. The cross section for gamma-ray production might be taken as a measure of the cross section for inelastic scattering. However, in some inelastic collisions—particularly those in which the high energy (14-Mev) neutrons from the Ra-Be source are involved—the residual nucleus may decay to the ground state by emitting several gamma-rays. Therefore a cross section for gamma-ray production is likely to be larger than a corresponding cross section for inelastic scattering. It was one purpose of the present experiments to determine by a somewhat more direct method a value for the inelastic scattering cross section of fast monochromatic neutrons falling on lead.

Recently, several authors have proposed theories of the interaction of energetic particles with a heavy nucleus which are based on thermodynamical considerations, treating the nucleus as a liquid drop.[6,7] According to Weisskopf,[6] monochromatic fast neutrons which have been scattered inelastically by a heavy element should exhibit a distribution of energies approximately Maxwellian. If the energy of the neutrons is initially P, the mean energy of the scattered neutrons should be given by $2(aP)^{\frac{1}{2}}$, where the constant "a" may be regarded as the average distance between the lowest levels of the scat-

* At present at Carnegie Institute, Department of Terrestrial Magnetism, Washington, D. C.
[1] D. E. Lea, Proc. Roy. Soc. **A150**, 637 (1935).
[2] Seaborg, Gibson, and Grahame, Phys. Rev. **52**, 408 (1937).
[3] D. C. Grahame and G. T. Seaborg, Phys. Rev. **53**, 795 (1938).
[4] Kikuchi, Aoki, and Husimi, Proc. Phys. Math. Soc. Japan **18**, 727 (1936).
[5] I. Nonaka, Phys. Rev. **59**, 681 (1941).
[6] V. Weisskopf, Phys. Rev. **52**, 295 (1937).
[7] V. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1939).

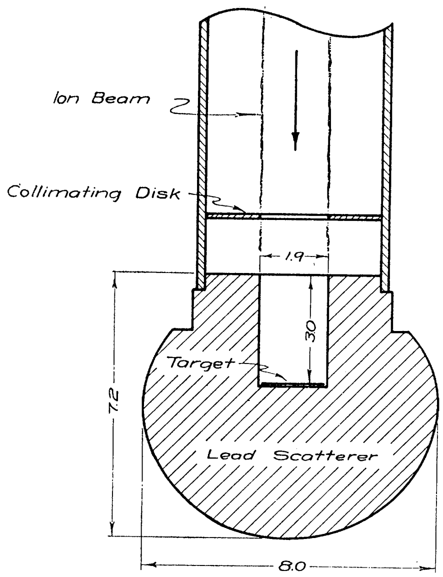

FIG. 1. Neutron source and scatterer. Dimensions are in cm. Cloud chamber 24 cm to right.

tering nucleus. The energy distribution of the inelastically scattered neutrons should be given by $N \cong KEe^{-E/T}$, where N is the number of neutrons per unit energy interval emitted at energy E, K is a constant, e is the base of the natural logarithms, and T is the temperature of the residual nucleus after the neutron has been emitted. The value of T is given by the equation $T=(aP)^{\frac{1}{2}}=\frac{1}{2}E_{\text{mean}}$. Hence if the distribution of the inelastically scattered neutrons is determined experimentally, T may be determined from the mean energy of this distribution, and the theoretical relation compared with that obtained by experiment.

The other purpose of the experiments to be described was to determine the energy distribution of the neutrons inelastically scattered by lead, so as to test the above theory, and to determine the important quantity "a" for a lead nucleus.

It should be remarked that in Weisskopf's first paper,[6] the restriction was made that the incident neutrons should have a kinetic energy greater than or equal to 3 Mev. However, in a later paper by Weisskopf and Ewing,[7] the restriction was lowered to include neutrons with incident energies as low as 1 Mev. The neutrons used in the present experiments had a range of energies from 2.19 to 2.89 Mev, so this condition was well met.

EXPERIMENT

Deuterons of 100 kv were obtained with a Cockcroft-Walton voltage doubler. They bombarded a thick target of heavy paraffin wax surrounded by a lead scatterer as shown in Fig. 1. Some of the neutrons which passed through the lead produced recoil protons in a cloud chamber, placed at 90° to the deuteron beam, and with its center 30.8 cm from the center of the target. The cloud chamber, which was of light construction, had a diameter of 13.5 cm, an effective (illuminated) depth of 4 cm, and was mounted so that the axis of the chamber was parallel to the deuteron beam. Care was taken to stand well away from the chamber during expansions. No magnetic analysis was used on the deuteron beam, and with this apparatus, instantaneous unresolved deuteron currents of 400 μa were obtainable. The lengths of the recoil proton tracks, and their angles with respect to the direction of the incident neutrons, were measured. About 39,000 expansions were photographed in this work. On these photographs, 1014 recoil protons were observed which satisfied our criteria as to distinctness, and which recoiled within less than 12.5° of the direction of the incident neutrons. Our results are based on a study of these recoil protons. Of the 39,000 expansions photographed, about 23,000 were photographed with the apparatus as in Fig. 1, while the remaining 16,000 were photographed with a thin (1-mm) walled aluminum cup as the target holder.

Since theory predicts[6,7] that the neutrons will suffer large energy losses in inelastic collisions, the cloud chamber was first filled with methane, so that its comparatively low stopping power would enable tracks of low energy to be measured. The chamber pressure was atmospheric, and the vapor employed was ethyl alcohol. The apparatus was set up as in Fig. 1, and 248 recoil protons were measured in methane. The stopping power of the methane was then obtained by inserting a Th C′ source, and measuring the range of the alpha-particles emitted, whose range in standard air is 8.53 cm. This gave a stopping power of 1.01. Unfortunately, the walls of the chamber became contaminated when this source was inserted, and it was necessary to take the chamber apart and clean it. This was done, the chamber reassembled, and 107 recoil protons were observed with a thin-walled aluminum cup in place of the lead scatterer as target holder. The stopping power of this methane was obtained by using Bonner's Q value of 3.31 Mev[8] for the deuteron-deuteron reaction. Bethe and Livingston have worked out a method for computing such Q values when the stopping power is known,[9] and this method may also be used to determine the stopping power if the Q value is known. This gave a stopping power of 0.96, a difference of about 5 percent from the previous value of 1.01. Such a variation becomes understandable when it is considered that the methane used comes from the commercial gas lines, which are themselves supplied at different times by different gas wells. If it is assumed that the stopping power of 0.96 is that of a gas with no ethane present, the addition of about 7 percent of ethane would give the stopping power of 1.01. A period of about a month elapsed between the times the gas was drawn from the mains, so that a variation of this amount in the percent of ethane present is not surprising.

However, since the data on the stopping power of the methane seemed slightly ambiguous, and since the data in methane seemed to indicate that the inelastically scattered neutrons would not have as low energies as was at first thought, it was decided that further data should be taken in a cloud chamber filled with a mixture of ethane and argon at atmospheric pressure. The vapor used was ethyl alcohol. When the chamber was filled with this mixture of ethane and argon, photographs were taken on alternate days with

TABLE I. *Compilation of data.*

Neutron Energy Mev	Observed Recoils with Pb	Observed Recoils Without Pb	Corrected Recoils with Pb	Corrected and Normalized Recoils Without Pb
		Methane		
0.5–0.6	4	0	4.4	0
0.6–0.7	12	3	13.9	4.2
0.7–0.8	11	2	13.5	3.9
0.8–0.9	9	4	11.8	5.2
0.9–1.0	12	1	16.8	2.3
1.0–1.1	10	2	15.1	4.9
1.1–1.2	12	0	19.1	0
1.2–1.3	8	1	13.8	2.9
1.3–1.4	7	1	13.0	3.1
1.4–1.5	13	2	26.2	6.7
1.5–1.6	14	3	31.0	11.1
1.6–1.7	10	3	24.6	12.5
1.7–1.8	13	1	35.4	4.6
1.8–1.9	9	3	27.4	16.2
1.9–2.0	9	4	32.0	18.6
2.0–2.1	11	8	45.0	59.6
2.1–2.2	16	7	77.8	54.9
2.2–2.3	16	10	95.0	103
2.3–2.4	14	25	106	249
2.4–2.5	18	25	164	453
2.5–2.6	16	1	225	31.4
2.6–2.7	4	1	86	48.0
2.7–2.8	0	0	0	0
		Ethane and Argon		
0.7–0.8	1	1	1.2	1.0
0.8–0.9	1	8	1.2	9.3
0.9–1.0	3	3	3.9	3.4
1.0–1.1	2	4	2.8	5.6
1.1–1.2	8	4	12.0	5.1
1.2–1.3	10	1	16.0	2.2
1.3–1.4	6	6	10.1	11.2
1.4–1.5	8	4	14.3	8.0
1.5–1.6	6	3	11.4	6.9
1.6–1.7	4	1	8.3	1.8
1.7–1.8	6	1	13.3	3.1
1.8–1.9	11	6	26.4	12.3
1.9–2.0	5	7	13.3	20.0
2.0–2.1	12	4	35.3	13.1
2.1–2.2	12	9	39.3	31.9
2.2–2.3	16	16	59.1	60.5
2.3–2.4	33	41	137	179
2.4–2.5	26	50	125	230
2.5–2.6	21	12	119	59.7
2.6–2.7	2	1	13.6	5.8
2.7–2.8	1	0	8.3	0

TABLE I.—*Continued.*

Neutron Energy Mev	Observed Recoils with Pb	Observed Recoils Without Pb	Corrected Recoils with Pb	Corrected and Normalized Recoils Without Pb
		Ethane		
0.7–0 8	2	2	2.3	2.3
0.8–0.9	3	3	3.7	3.7
0.9–1.0	3	1	3.8	1.3
1.0–1.1	2	4	2.8	5.5
1.1–1.2	2	0	2.9	0
1.2–1.3	1	0	1.5	0[1]
1.3–1.4	6	3	9.9	5.0
1.4–1.5	3	2	5.2	3.5
1.5–1.6	3	1	5.5	1.8
1.6–1.7	4	2	7.8	3.9
1.7–1.8	2	2	4.1	4.1
1.8–1.9	6	4	13.3	8.9
1.9–2.0	3	0	7.3	0
2.0–2.1	7	3	16.6	8.0
2.1–2.2	6	7	17.2	20.1
2.2–2.3	13	11	40.9	34.7
2.3–2.4	22	41	77.2	144
2.4–2.5	33	38	132	152
2.5–2.6	16	15	71.7	67.3
2.6–2.7	6	0	29.3	0
2.7–2.8	1	0	5.9	0

[8] T. W. Bonner, Phys. Rev. 59, 237 (1941).

[9] M. R. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 289 (1937).

the lead scatterer and with the thin-walled aluminum cup as the target holder. The stopping power of this mixture was evaluated from the distribution obtained when there was no lead scatterer around the target, Bonner's Q value of 3.31 Mev was used just as before. Since the stopping power of the mixture seemed to change slightly about halfway through this run, the data were evaluated in two parts. For the first part we obtained the stopping power 1.30, and for the second part, the stopping power 1.31. Since the stopping powers are very nearly the same, these are listed together in our results under the title ethane and argon, although the appropriate stopping power was used in evaluating each part of this run. In all, 376 recoils were observed during this run, 194 being observed when there was lead surrounding the target, and 182 when there was no lead.

These results showed that it would be desirable to use a gas with an even higher stopping power in the cloud chamber. The cloud chamber was consequently rebuilt to obtain expansion ratios high enough for ethane, and further data were taken with ethane, and ethyl alcohol and water vapor in the chamber. Data were taken on alternate days with the lead scatterer and with the aluminum cup as the target holder, and the stopping power evaluated from the distribution

TABLE II. *Total data, corrected and normalized.*

Neutron Energy Mev	Corrected Recoils with Pb	Normalized and Corrected Recoils Without Pb
0.5–0.6	4.4	0
0.6–0.7	13.9	4.2
0.7–0.8	17.0	7.2
0.8–0.9	16.7	18.2
0.9–1.0	24.5	7.0
1.0–1.1	20.7	16.0
1.1–1.2	34.0	5.1
1.2–1.3	31.3	5.1
1.3–1.4	33.0	19.3
1.4–1.5	45.7	18.2
1 5–1.6	47.9	19.1
1.6–1.7	40.7	18.2
1.7–1.8	52.8	11.8
1.8–1.9	67.1	37.4
1.9–2.0	52.6	38.6
2.0–2.1	96.9	80.7
2.1–2.2	134	107
2.2–2.3	195	198
2.3–2.4	320	572
2.4–2.5	421	835
2.5–2.6	416	158
2.6–2.7	129	53.8
2.7–2.8	14.2	0

obtained when there was no lead scatterer around the target. In all, 283 recoils were observed at this stopping power, 144 with the lead scatterer, and 139 without it.

Altogether, 586 tracks were measured with the lead, and 428 without it.

Our results are shown in Table I. The observed and corrected numbers of tracks are shown in each energy interval. The corrections are to allow for the varying probability of observation of a track of length L in a cloud chamber whose diameter is 13.5 cm, and to allow for the variation of neutron proton collision cross section with energy. If r is the radius of the chamber, then in general, we have that

$$P=[1/\pi r^2][\pi r^2-L(r^2-L^2/4)^{\frac{1}{2}}-2r^2\sin^{-1}(L/2r)]$$

where P is the number of tracks of length L observed in the chamber of area πr^2, divided by the number of tracks of length L that would have been observed in an equal area of a chamber whose radius was infinite. The observed number of tracks is multiplied by $1/P$. The neutron proton collision cross sections were taken from the work of Kittel and Breit,[10] and the factor we have used is the reciprocal of these cross sections, normalized to 1 at 0.5 Mev. In addition, after the above corrections were made, the corrected number of tracks obtained in each energy interval without the lead was multiplied by a factor such as to make the total number of tracks with the lead, and without it, equal. For example, the corrected number of tracks observed with the lead when methane was in the chamber was 1097, and the corrected number of tracks observed without lead was 688. The number of tracks in each energy interval obtained without the lead was therefore multiplied by the factor $1097/688=1.6$, and the result listed under the column headed "corrected and normalized recoils without lead." A similar procedure was carried out for the data obtained with ethane, and with ethane and argon in the chamber. This normalizing procedure assumes that the total number of neutrons entering the cloud chamber is nearly the same with the lead as without it. The measured tracks without the lead scatterer are mainly due to

[10] C. Kittel and G. Breit, Phys. Rev. 56, 747 (1939).

neutrons coming directly from the source, but include some scattered by the aluminum cup and other bodies in the neighborhood. If we neglect neutrons scattered by the walls of the aluminum cup, the above assumption would be true if the lead scattered as many neutrons into the chamber as out of it. This is believed to be the case for elastically scattered neutrons, since as will be shown later they are mostly scattered through angles less than about 50°. The non-symmetrical distribution of the neutrons emitted in the deuteron-deuteron reaction will therefore not have much effect. It is true that inelastic scattering is thought to be spherically symmetrical, but since the neutrons that have been inelastically scattered are only about 12.5 percent of the total number, the non-symmetrical distribution of the neutrons coming from the deuteron-deuteron reaction will affect the total number but slightly. The total corrected number of tracks observed with the lead was 2230 on 23,000 photographs, and the total corrected number of tracks without the lead was 1797 on 16,000 photographs. Thus the number per photograph was 0.10 with the lead, and 0.11 without it. The agreement of these numbers supports the assumption that the total corrected number of tracks is not changed by the lead scatterer.

Table II shows all of our data, which have been corrected and normalized as described above. From these data, we obtain the distribution of the neutrons inelastically scattered by the lead as follows. The numbers of tracks in each energy interval obtained without the lead were subtracted from the number obtained with the lead in the corresponding energy interval. The differences obtained in this way were taken to be the number of neutrons inelastically scattered by the lead, and are given in Table III. Above 2.0 Mev, the number cannot be obtained in this way, since the number of elastically scattered neutrons begins to be appreciable. The lowest energy which a 2.19-Mev neutron could appear to have with our measurement criteria is 2.07 Mev. Since the probable error in the energy of a track due to all causes is about 100 kv, it is fairly certain that tracks with energies below 2.0 Mev are due to neutrons that have lost energy in an inelastic collision. Although the differences listed in Table III seem to show a group structure, with several rather sharp maxima and minima, this is thought to be statistical, as the fluctuations are barely outside the probable error. The data of Table III are accordingly given graphically in Fig. 2, plotted in 200-kv intervals to smooth out statistical fluctuations. The probable errors in the points are given by the vertical bars. The distribution has been extrapolated smoothly to the origin from 0.6 Mev. Since the neutrons from the deuteron-deuteron reaction are not exactly monochromatic (ranging from 2.19 to 2.89 Mev), the incident neutrons were all assumed to have the mean energy of 2.5 Mev, and the experimental distribution extrapolated to that energy. The behavior of the experimental curve beyond 1.8 Mev is somewhat doubtful. From 1.8 to 2.0 Mev the curve does seem to drop somewhat, but the probable errors are so large in this region that it might well be doubted if this has any real significance. Consequently the possibility that the distribution continues to rise as it approaches 2.5 Mev cannot be ruled out.

TABLE III. *Distribution of inelastically scattered neutrons.*

Neutron Energy Mev	Neutrons Inelastically Scattered by the Pb
0.5–0.6	4.4
0.6–0.7	9.7
0.7–0.8	9.8
0.8–0.9	−1.5
0.9–1.0	17.5
1.0–1.1	4.7
1.1–1.2	28.9
1.2–1.3	26.2
1.3–1.4	13.7
1.4–1.5	27.5
1.5–1.6	28.8
1.6–1.7	22.5
1.7–1.8	41.0
1.8–1.9	29.7
1.9–2.0	14.0

According to Weisskopf, this distribution should be given approximately by

$$N \cong KEe^{-E/T}$$

where the symbols have been defined previously. This curve is also shown in Fig. 2, plotted with two different values of T. In one, T was calculated from Weisskopf's theoretical relation,

$$2T = E_{\text{mean}}.$$

Here, E_{mean} is the mean energy of the neutrons

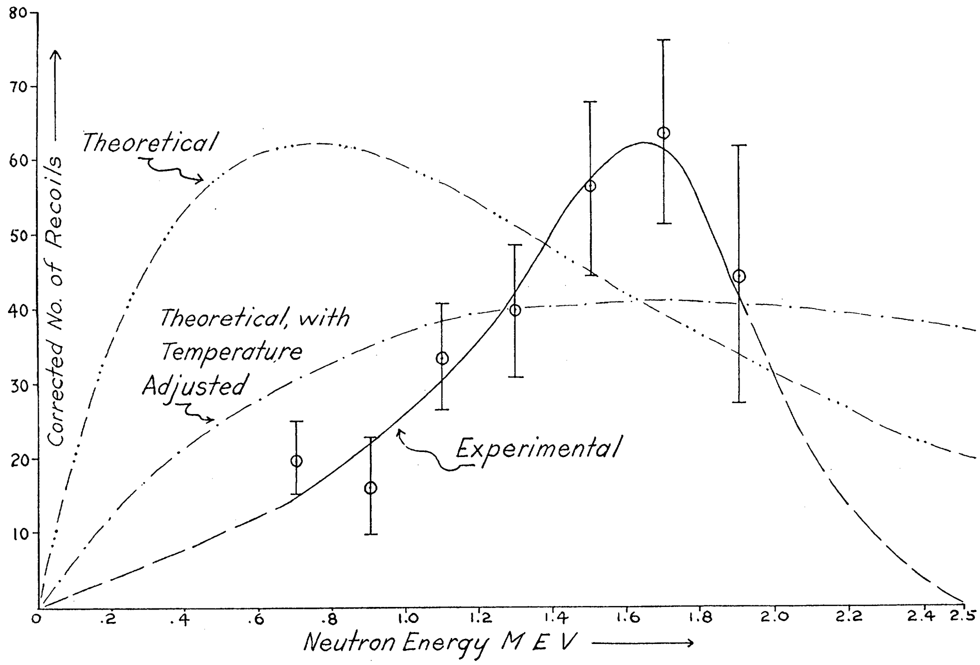

FIG. 2. Distribution of inelastically scattered neutrons.

inelastically scattered by the lead, taken to be 1.5 Mev under the assumption that the experimental distribution falls to zero as the energy approaches 2.5 Mev. In the other theoretical curve shown, T was arbitrarily adjusted so as to make the maxima of the experimental and theoretical distributions agree. The value of the constant K was also reduced by a factor of $\frac{2}{3}$ in order to come as close to all the experimental points as possible. It is interesting to note that the value of T necessary to make the maxima agree corresponds to a mean energy of the inelastically scattered neutrons of 3.4 Mev, which is larger than the energy of the incident neutrons!

In the light of the disagreement between the experimental and theoretical distributions, the value of the constant "a" seems to be of little interest. However, it was calculated from the theoretical relation

$$E_{\text{mean}} = 2(aP)^{\frac{1}{2}}.$$

If P is taken as 2.5 Mev, this gives a value of "a" $=0.2$ Mev, while Weisskopf estimates that "a" should lie between 0.05 and 0.2 Mev.

It should be noted that Lea[1] has estimated that the average energy of the gamma-rays excited when Ra-Be neutrons pass through lead is of the order of 1.5 Mev, while Gibson, Grahame, and Seaborg[2] estimate that it is of the order of, or less than, 1 Mev. The mean energy of the neutrons emitted from a Ra-Be source is about 4.5 Mev,[11] so this means, that on the average, they lose about $1.3/4.5=0.29$ of their energy in an inelastic collision. This, of course, assumes that the excited nucleus loses its energy by emitting one large instead of several small gamma-rays, which may or may not be true. The mean energy of the neutron distribution we have observed comes at about 1.5 Mev, so that according to our results the neutrons should lose on the average $1.0/2.5=0.40$ of their energy. From the shape of the theoretical curve given in Fig. 2, it is evident that they should lose a much higher fraction of their energy.

If the distribution of inelastically scattered neutrons actually falls to zero at 2.5 Mev, the distribution is at least of the form expected, in spite of the fact that the most probable energy of an inelastically scattered neutron is considerably larger than thought. However, if, as seems possible from these results, the distribution

[11] J. R. Dunning, Phys. Rev. **45**, 586 (1934).

continues to rise as it approaches 2.5 Mev, the fact would have far-reaching theoretical implications. In particular, it would be difficult to reconcile such a result with the idea of the long existence of the compound nucleus. If the compound nucleus exists for a long time in comparison, say, to the transit time of the incident neutron across the nucleus, it is difficult to see how the incident neutron could be reemitted with a very high energy, since this energy would be shared by two hundred other particles. Our results could be understood, however, if the compound nucleus exists only long enough for the energy of the incident neutron to be shared by a few particles before the neutron is reemitted, with a comparatively high energy. In fact, a sort of "local heating" of the nucleus is implied both by these results, and by the gamma-ray results quoted above.

From these experiments, it is also possible to calculate the inelastic scattering cross section for 2.5-Mev neutrons from lead, provided that we assume that the scattering is spherically symmetrical. In that case, the cross section for inelastic scattering is given to a first approximation by the following formula:

$$B-A=(B-AK)e^{-nkx}. \qquad (1)$$

Here, A is the corrected number of neutrons inelastically scattered by the lead (see Fig. 2); B is the corrected number of neutrons obtained when lead surrounded the target, the background having been subtracted, and the distribution from 0.6 to 0 Mev taken from Fig. 2; K is a factor arising from the asymmetry of the neutrons coming from the deuteron-deuteron reaction (to be discussed more fully later); e is the base of the natural logarithms; n is the number of lead nuclei per cc; k is the cross section for inelastic scattering; and x is the average thickness of lead through which the neutrons pass. We assume the total *number* of neutrons reaching the cloud chamber is unaffected by elastic scattering (as many scattered away from the chamber as toward it); we neglect the variation in solid angle which the chamber subtends at different parts of the scatterer (i.e., we assume that both the scattered and unscattered neutrons start at the center of the target. That this is permissible is shown by the fact that a calculation in which the single point source assumed for the scattered neutrons was replaced by four point sources symmetrically distributed in the scatterer gave a value of the inelastic scattering cross section only about 5 percent different from that obtained when a single point source at the center was assumed); and we assume that the scatterer is in the shape of a sphere, with a cylindrical hole above the target in it.

The spatial distribution of the neutrons emitted in the deuteron-deuteron reaction is given by

$$N_\theta=N_{90}(1+0.7\cos^2\theta),$$

where θ is the angle between the forward direction of the deuteron beam and the direction of the emitted neutron in a coordinate system in which the center of gravity is at rest, and N_θ is the number of neutrons emitted per unit solid angle at angle θ.[12–14] Neutrons will be scattered inelastically by the lead into the chamber from the forward and backward directions as well as at right angles to the deuteron beam. However, when the lead scatterer is not present, only neutrons emitted at right angles to the deuteron beam will reach the chamber. It is evident therefore, that the number of neutrons inelastically scattered into the chamber by the lead is larger than would be the case if the distribution of neutrons from this reaction were symmetric. To correct for this, we transform the above Eq. (1) into laboratory coordinates, and average it over the surface of a sphere from $\varphi=162.4°$ to $\varphi=0°$. The value $\varphi=180°-162.4°=17.6°$ corresponds to the angle between the center of the target, and the edge of the cylindrical cavity above the target. In laboratory coordinates, the distribution of the neutrons will be given by

$$N_\varphi=C[1+0.7\cos^2\{\varphi+\sin^{-1}(v_{\text{c.g.}}\sin\varphi/v_0)\}]\times\sin\varphi d\varphi. \qquad (2)$$

Here, N_φ is the number of neutrons given off between the angles φ and $\varphi+d\varphi$, φ is the angle between the forward direction of the deuteron

[12] Kempton, Browne, and Maasdorp, Proc. Roy. Soc. **A157**, 386 (1936).

[13] Haxby, Allen, and Williams, Phys. Rev. **55**, 143 (1939).

[14] Huntoon, Ellett, Bayley, and Van Allen, Phys. Rev. **58**, 97 (1940).

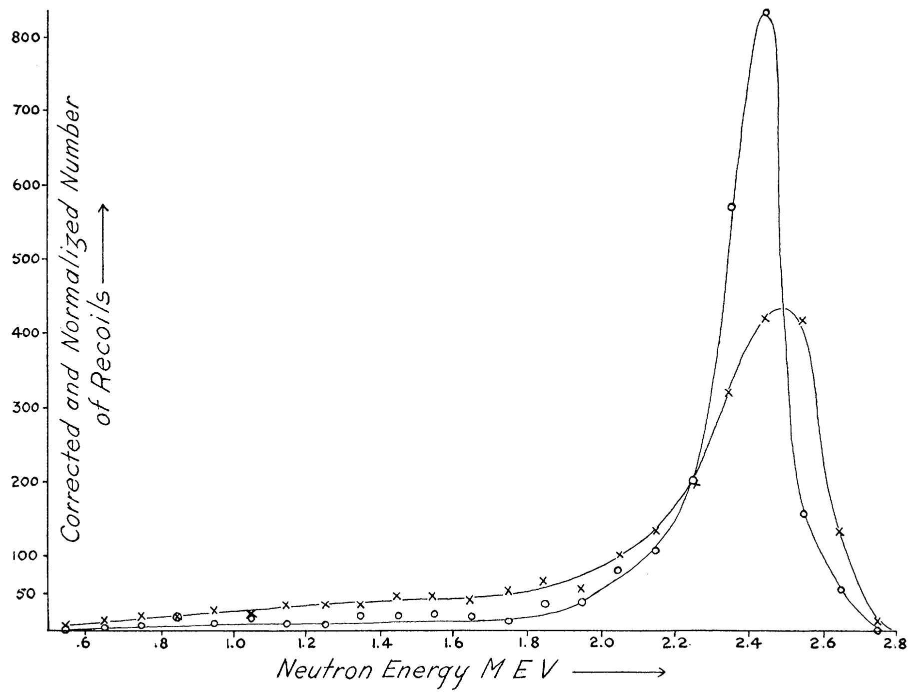

FIG. 3. x = data obtained with lead. o = data obtained without lead.

and the direction of the emitted neutron in laboratory coordinates, C is a constant, $v_{c\ g.}$ is the velocity of the center of gravity of the system, easily calculated from the masses of the particles involved and the bombarding energy, v_0 is the velocity of the emitted neutron in the center of gravity system, also easily calculated from the masses and the known Q value for the reaction. The average value desired is just

$$N' = \left[\int_0^{162.4^\circ} N_\varphi\right] \Big/ \left[\int_0^{162.4^\circ} 2\pi \sin\varphi d\varphi\right]. \quad (3)$$

The numerator of Eq. (3) may be integrated after a trigonometric substitution, and we obtain the value $N' = 1.2$. The number of neutrons that would have been scattered into the chamber if the distribution had been symmetric is just $(1/1.2)A$. Hence, in Eq. (1), we subtract $(1-1/1.2)A$ from both A and B. Let $(1-1/1.2) = K$. Since KA is subtracted from both A and B, it has no effect on the left-hand side of Eq. (1). Using all the experimental results, and assuming that the distribution approaches zero as the energy approaches 2.5 Mev, we obtain the value $k = 1.31 \pm 0.53 \times 10^{-24}$ cm^2 from Eq. (1). If, however, the distribution continues to rise as the energy approaches 2.5 Mev, the value $k = 1.81 \pm .61 \times 10^{-24}$ cm^2 is obtained for the inelastic scattering cross section. These values may be compared with the value of Seaborg, Gibson, and Grahame[2] of $1.22 \pm 0.17 \times 10^{-24}$ cm^2, and the value obtained by Lea[1] of $2.16 \pm 0.22 \times 10^{-24}$ cm^2, both of which where obtained with the unhomogeneous neutrons emitted from a Ra-Be source, and while studying the gamma-rays emitted. Recently Nonaka,[5] using deuteron-deuteron neutrons of about 2.5 Mev, obtained a value of $0.63 \pm 0.2 \times 10^{-24}$ cm^2 from a study of the gamma-rays emitted from the lead scatterer. However, it should also be noted that Nonaka's value depends on an assumed efficiency of a Geiger counter. As these efficiencies depend in general upon the gamma-ray energy, which is unknown in his case, his small value may be somewhat in error.

The fact that cross sections obtained from a study of the gamma-rays emitted from the scatterer might be expected to be larger than those obtained from a direct study of the scattered neutrons (since several gamma-rays may be emitted per inelastic collision) tends to give more weight to the assumption that the distribution falls to zero as the energy approaches 2.5 Mev, as this assumption yielded the smaller value of scattering cross section.

It is planned at present to expose some photographic plates to monochromatic 4-Mev deuteron-deuteron neutrons scattered by lead. At these higher energies, it should be possible definitely to settle the point as to whether or not the distribution of the inelastically scattered neutrons continues to rise as it approaches the energy of the incident neutrons.

Conclusions concerning elastic scattering of neutrons by lead may also be drawn from these experiments. At present, data concerning elastic scattering of neutrons by lead are scanty. Weisskopf and Ewing[7] quote some unpublished results of Bacher which indicate that at least 95 percent of the scattering of neutrons from lead is inelastic. There is some theoretical evidence that elastic scattering is especially large in the forward direction,[15] and recently a preponderance of small angle scattering of an unspecified nature has been reported.[16,17] By small angles, we mean angles under about 50°. Our data also show that considerable elastic scattering takes place, since the main group of the curve is considerably broader with the lead scatterer than with the aluminum cup. This is what would be expected if elastic scattering were appreciable, since the energy of the neutrons emitted in the deuteron-deuteron reaction depends on the angle of emission according to the following equation

$$E_n-(\sqrt{2}/2)(E_nE_i)^{\frac{1}{2}}\cos\varphi-(E_i+3Q)/4=0,$$

where E_n is the energy of the neutron which comes off at angle φ with respect to the incident deuteron in laboratory coordinates, E_i is the energy of the incident deuteron, and Q is the energy evolved in the reaction. This broadening is well shown in Fig. 3, which is a graph of the data given in Table II. Note that in addition to being broadened, the maximum of the 2.5-Mev group of neutrons is shifted appreciably to higher energies by the presence of the lead, which is again what would be expected to occur if elastic scattering took place, since there is more lead in front of the target than behind it, and since the more energetic neutrons come off in the forward direction.

The fact that the neutron spectrum does not extend beyond 2.8 Mev shows that elastic scattering cannot be spherically symmetrical. If it were, then neutrons would be scattered through angles as great as 90°, and the 2.89-Mev neutrons given off in the forward direction with respect to the deuteron beam would be able to reach the cloud chamber. On the other hand, the highest energy neutrons observed, which are 2.8-Mev, would have come off at 39° with respect to the incident deuterons. This means that elastic scattering at angles greater than $90°-39°=51°$ is not appreciable. This is in qualitative agreement with theory,[15] and also agrees with the results and Wakatuki and Kikuchi,[16,17] provided the assumption is made that the large cross sections for scattering in the forward direction which they observed are due to elastic scattering. Since they used an electroscope as the detector of their scattered neutrons, they were unable to distinguish between elastic and inelastic scattering. If this interpretation is made of the results of Wakatuki and Kikuchi, the assumption we have made that inelastic scattering is spherically symmetrical is justified, since the cross sections they observed were constant for the scattering angle greater than about 50°.

In conclusion, it is a pleasure to acknowledge the continued interest and suggestions of Professor Wilson, Professor Bonner, and Dr. Bennett, and to thank Professor Heaps for several helpful discussions of the problem. The assistance of Mr. Van der Henst and Mr. De Vries is also gratefully acknowledged.

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