Elastic and Inelastic Scattering of Fast Neutrons*

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The scattering of the 2.5 Mev $d-d$ neutrons by C, Al, Fe, Cu, Zn, and Pb was investigated by analyzing the distribution in energy of recoiling α-particles in an ionization chamber. Measurements were carried out for scattering angles of the neutrons of 45° and 100°. The differential cross section for elastic scattering was measured, and the amount of inelastic scattering could be estimated. The elastic scattering showed a strong anisotropy whereas the inelastic scattering was roughly the same for the two scattering angles. The ratio of elastic to inelastic scattering was found to be appreciably larger in C, Al, and Pb than in Fe and Cu.

I. INTRODUCTION

THE scattering of fast neutrons by nuclei is at least partly inelastic in the case of medium and heavy masses like Fe, Ag, and Pb. This was first shown by Danysz *et al.*[1] and then confirmed by Fermi and collaborators[2] and by other authors.[3] Using a radon-beryllium neutron source one finds a change in the radioactivity induced in various detectors when different substances are interposed between the source and the detector. Detectors sensitive to slow neutrons (of a few ev energy) like Ag and Rh show an increase in activity, whereas detectors such as Si and Al sensitive to fast neutrons of some Mev energy show a decrease. A similar effect produced by light nuclei such as carbon and silicon can be explained perhaps by the energy loss in elastic collisions, which in a scatterer of mass A may produce an energy loss of $4A/(A+1)^2$ times the initial neutron energy. But the slowing down by heavy nuclei must be due to inelastic collisions, that is, excitation of the nucleus to some excited state while the neutron loses the corresponding amount of kinetic energy. The excited nucleus may lose its energy by emitting γ-rays or internally converted electrons, going down to its normal state. Such γ-rays from the "non-capture" excitation of nuclei by fast neutrons have actually been found by Lea,[4] by Kikuchi, Aoki, and Husimi[5] and by others.[6]

Using the neutrons from a Po-Be source which may have an average energy of about 5 Mev Lea found appreciably more γ-rays from Pb than from Fe, and many less from carbon. Kikuchi, Aoki, and their collaborators used the homogeneous neutrons of 2.5 Mev energy from the $d-d$ reaction and got fewer γ-rays from Al and Pb than from Fe and Cu. A similar result was obtained by Kallmann and Kuhn.[6] Grahame and Seaborg[3] concluded from their experiments with different detectors that high energy neutrons of more than 4 Mev produce relatively more γ-rays in Pb, compared for example with Fe and Cu, than do "medium" fast neutrons of about 1 Mev. Hudspeth and Bonner[7] analyzed in a Wilson cloud chamber the neutrons from the $d-d$ reaction scattered by 3 cm of Pb, by measuring the distribution in energy of the protons in the forward direction. They concluded from their results that only 10–15 percent of the initial neutrons of 2.5 Mev made inelastic collisions in the lead with energy losses of from

* A preliminary report of the experiments has been given at the Washington meeting, 1941, see Phys. Rev. **59**, 917 (1941).
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[1] M. Danysz, J. Rotblat, L. Wertenstein, and M. Zyw, Nature **134**, 970 (1934).
[2] Amaldi, d'Agostino, Fermi, Pontecorvo, Rasetti, and Segrè, Proc. Roy. Soc. **A149**, 533 (1935).
[3] W. Ehrenberg, Nature **136**, 870 (1935); J. Rotblat and M. Zyw, Nature **137**, 185 (1936); P. I. Lukirsky and T. Careva, Comptes rendus Acad. des sci. de l'U.R.S.S. **3**, 411 (1936); C. H. Collie and J. H. E. Griffith, Proc. Roy. Soc. **A155**, 434 (1936); G. T. Seaborg, G. E. Gibson, and D. C. Grahame, Phys. Rev. **52**, 408 (1937); D. C. Grahame and G. T. Seaborg, Phys. Rev. **53**, 795 (1938); E. T. Booth and C. Hurst, Proc. Roy. Soc. **A161**, 248 (1937); W. D. Allen and C. Hurst, Proc. Phys. Soc. **52**, 501 (1940). See also Bethe's report, Rev. Mod. Phys. **9**, 156 (1937), containing the complete literature and its critical discussion up to that time.
[4] D. E. Lea, Proc. Roy. Soc. **A150**, 637 (1935).
[5] S. Kikuchi, K. Husimi, and H. Aoki, Proc. Phys. Math. Soc. Japan **18**, 188 (1936); **19**, 369 (1937).
[6] R. Fleischmann, Zeits. f. Physik **97**, 242 (1935); H. Kallmann and E. Kuhn, Naturwiss. **26**, 106 (1938); Grahame and Seaborg, reference 3; I. Nonaka, Phys. Rev. **59**, 681 (1941).
[7] E. Hudspeth and T. W. Bonner, Phys. Rev. **53**, 928 (1938).

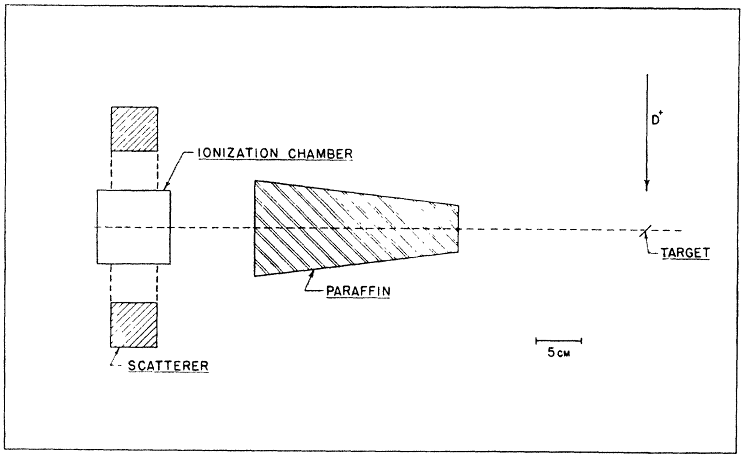

FIG. 1. Experimental arrangement for investigating the neutrons scattered through 100°.

0.5 to 1.3 Mev. Kikuchi, Aoki, and Wakatuki[8] have studied the angular distribution of monoenergetic neutrons of about 3 Mev scattered in C, Al, Fe, Cu, Sn, Pb, Bi, and found a large anisotropy increasing with atomic mass. The scattering was much stronger in the forward direction than at larger scattering angles, but their experiments do not enable one to distinguish whether the scattered neutrons have lost energy or not. We shall come back to these results in the discussion. Bacher[9] concluded from his experiments that neutrons of high energy from a Be target bombarded by deuterons, and detected by the radioactivity of Al were "elastically" scattered to an appreciable extent by C, Cu, and Pb in the forward direction only, but no quantitative data on the relative amounts of elastic and inelastic scattering were given.

It was hoped that more quantitative information could be obtained by using the experimental arrangement in this laboratory which allows one to analyze the distribution in energy of neutrons in a large pressure ionization chamber.[10]

II. EXPERIMENTAL METHOD

In order to distinguish between elastically and inelastically scattered neutrons the distribution in energy of recoil particles in an ionization chamber was analyzed. Baldinger, Huber, and Staub[11] first pointed out that the distribution in energy of fast neutrons could be determined by this method provided that the maximum range of the recoil particles is small compared with the size of the chamber. The relation between the two distributions is particularly simple if the angular distribution of the neutrons scattered by the gas in the chamber is isotropic in the center of mass system. Since this condition is known[10] to hold in hydrogen and deuterium for 2.5-Mev neutrons over a wide range of angles, it would appear that either of these gases would be appropriate for filling an ionization chamber if one wants to determine the distribution in energy of fast neutrons. Previous measurements[10] have shown, however, that considerable difficulties arise if one increases the stopping power of the gas to values at which the range of the recoil protons or deuterons from 2.5-Mev neutrons is small compared to the size of the chamber. γ-rays occurring when neutrons are scattered inelastically may produce electrons which give rise to ionization pulses indistinguishable from those due to low energy recoil particles. A further difficulty is the relatively long time it takes to collect the ions in the chamber even with very high collecting fields. The long collecting times reduce the resolving power for different neutron energies to such an extent that it cannot be hoped to obtain a clear analysis of the neutron energies.

The present experiments were carried out, therefore, by observing recoiling helium nuclei. The use of helium had, however, other disadvantages. The angular distribution of 2.5-Mev neutrons scattered by helium is known[10] to be

[8] S. Kikuchi, H. Aoki, and T. Wakatuki, Proc. Phys. Math. Soc. Japan, **21**, 232, 410, 656 (1939).
[9] R. F. Bacher, Phys. Rev. **57**, 352 (1940).
[10] H. H. Barschall and M. H. Kanner, Phys. Rev. **58**, 590 (1940).
[11] E. Baldinger, P. Huber, and H. Staub, Helv. Phys. Acta **11**, 245 (1938).

anisotropic (cf. Fig. 2), and it is to be expected that the scattering will be anisotropic also for lower neutron energies. Unfortunately the angular distribution is so far known only for neutrons between 2- and 3-Mev energy. Furthermore, the neutron-helium scattering cross section varies strongly with neutron energies between 0.5 and 2 Mev. These circumstances make it impossible to give a quantitative analysis of the inelastically scattered neutrons, but the present experiments enable one to estimate the amount of inelastic scattering and to determine the differential cross section for elastic scattering for different scattering angles.

In all the experiments the 2.5-Mev neutrons emitted at right angles to the deuteron beam in the $d-d$ reaction were used. The deuterons were accelerated by voltages of 200 to 300 kv. The target consisted of D_2O ice. The various kinds of ions in the deuteron beam were not separated.

The recoiling α-particles were produced in an ionization chamber with multiple collecting electrodes.[10] The chamber was filled with 5.5 atmos. of helium. The collecting field was 1700 volts/cm. The chamber was 8 cm high and 8 cm in diameter.

The ionization pulses were amplified by means of a linear amplifier with strong inverse feedback. In some of the experiments the pulses were recorded on photographic paper with a torsion type oscillograph. In other experiments pulses above a definite size were selected by a thyratron relaxation oscillator with long time constants and counted by a scale-of-two circuit connected to a mechanical counter.

The gain of the amplifier and its linearity were checked with the help of artificial pulses of variable size as described before.[12] The calibration of the pulses recorded by the oscillograph in terms of ionization was accomplished by measuring the maximum recoil pulses from 2.5-Mev neutrons. These pulses were compared with standard pulses so that no new calibration was necessary when the gain of the amplifier was changed.

Since the frequency response of the mechanical oscillograph was not exactly the same as that of the selector stage of the counting circuit this comparison was not valid when the pulses were counted by the scaling circuit. For these experiments the grid bias setting of the selector tube was calibrated in terms of ionization energy by the following procedure. Both recoil pulses and artificial pulses were photographed and counted simultaneously. By coupling the two circuits the breakdown of the selector stage was recorded simultaneously with the acting pulses. The coupling was arranged so that the pulses counted by the selector stage were recorded considerably larger than the maximum recoil pulses which were not counted. It was noted at which voltage setting of the pulse generator a part, for instance half, of the artificial pulses were counted. On the photographic record the maximum size of recoil pulses which were not counted was measured and compared with the photographed standard pulses. In this way the minimum energy to which a pulse had to correspond in order to be counted was determined. During the measurements this value was checked frequently by the use of standard pulses. Variations in the standard pulse voltage at which half the pulses were rejected by the selector did not exceed 2 percent during a measurement.

The protons from the $d-d$ reaction were used for monitoring the number of neutrons. The protons emitted at a right angle with respect to the deuteron beam into a known solid angle entered an ionization chamber connected to a linear amplifier. The pulses were counted by means of a scale-of-eight and a mechanical counter.

The experimental arrangement for the scattering experiments is shown schematically in Fig. 1. The scatterers had the form of rings with square cross sections. They had an inner diameter of 16.4 cm and were 5 cm thick. The rings were castings except in the case of carbon where graphite was used. A truncated cone of paraffin, 22 cm long, was interposed between the target and the ionization chamber in order to reduce the number of neutrons not scattered in the ring, but detected in the chamber. The paraffin was placed so that all the neutrons coming from the target, which could reach the chamber directly, had to pass through it. The neutrons could get to

[12] M. H. Kanner and H. H. Barschall, Phys. Rev. 57, 372 (1940).

the scatterer, however, without passing through the paraffin. When the scatterer was in the position shown in Fig. 1 the mean scattering angle of the neutrons was 100°. By moving both the scatterer and the paraffin closer to the target the scattering angle could be reduced to 45°. Since the scatterer subtended a finite angle at the target there was a spread in energy of the neutrons on account of the variation of the angle of emission of the neutrons with respect to the deuteron beam. This uncertainty in neutron energy amounted to about ± 0.10 Mev for the distant position of the ring scatterer and to ± 0.15 Mev for the close position of the scatterer. The large dimensions of the scatterer and the detector also introduced an appreciable uncertainty in the scattering angles of the neutrons, approximately $\pm 20°$ for the position in which the mean scattering angle was 100°, and $\pm 10°$ for the position corresponding to a mean scattering angle of 45°.

In the first part of the experiments the distribution in energy of the recoiling α-particles due to scattered neutrons was measured. Photographic records were taken alternately with and without the ring scatterer, the number of protons counted being the same in the two cases. The records were evaluated by counting the number of pulses ending in each of about twenty deflection intervals. The difference in the numbers in each interval obtained with and without scatterer, gives the distribution of α-particles due to neutrons scattered by the ring.

If one assumes that the α-particles of highest energies are due to elastically scattered neutrons, the cross section $\sigma(\vartheta)$ for elastic scattering through

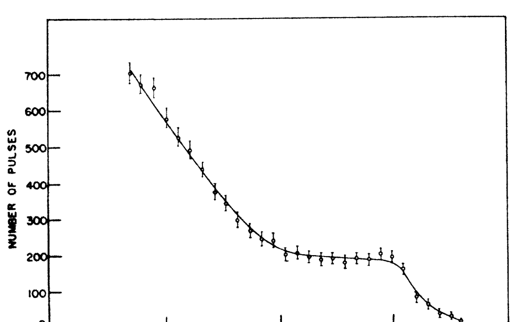

FIG. 2. Distribution in energy of recoiling α-particles knocked on by 2.5-Mev neutrons from the $d-d$ reaction.

an angle ϑ per unit solid angle is given by[13]

$$\sigma(\vartheta)=\frac{A\cdot E_m}{\sigma_{\mathrm{He}}Nn_1n_2\Delta E\int dV_1dV_2/r^2},$$

A being the number of α-particles in the energy interval between $E_m-\Delta E$ and E_m, E_m the maximum recoil energy due to 2.5-Mev neutrons, σ_{He} the total scattering cross section of helium (4π times the differential cross section per unit solid angle) for backward scattering of 2.5-Mev neutrons, N the number of neutrons impinging upon 1 cm^2 of the scatterer, n_1 the number of nuclei per cm^3 of the scatterer, n_2 the number of nuclei per cm^3 in the ionization chamber, r the distance between a volume element dV_1 of the scatterer and a volume element dV_2 of the chamber. The number N can be computed from the number of protons counted, the known[14] yield of protons and neutrons in the $d-d$ reaction and the geometry of the apparatus. It should be pointed out, however, that errors in the previous measurement[10] of σ_{He} and in the present measurement of N can be expected to cancel, since a very similar experimental set-up was used in both experiments.

In the second part of the experiments three quantities were measured: the number of recoil particles N_1 counted without paraffin and without scatterer (due to direct neutrons), the number of recoil particles N_2 with the paraffin interposed, but without scatterer, and the number of recoil particles N_3 with both the paraffin and the scatterer present. The three numbers were reduced to the same number of protons. The background of the chamber due to natural radioactivity of the chamber was subtracted from these numbers. If only recoil particles of highest energies are counted, $\sigma(\vartheta)$ may be obtained similarly as in the preceding formula by

$$\sigma(\vartheta)=\frac{V_2\cdot r_1^2}{R^2n_1\int dV_1dV_2/r^2}\cdot\frac{N_3-N_2}{N_1},$$

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[13] We are much indebted to Professor J. A. Wheeler and Mr. P. Olum for numerical evaluation of the integral appearing in the above formula. The calculation was accomplished by expanding $1:r^2$ into spherical harmonics on a four-dimensional sphere, and using the zero- and second-order terms in the expansion (the odd members of the expansion vanish upon integration).

[14] R. Ladenburg and M. H. Kanner, Phys. Rev. **52**, 911 (1937).

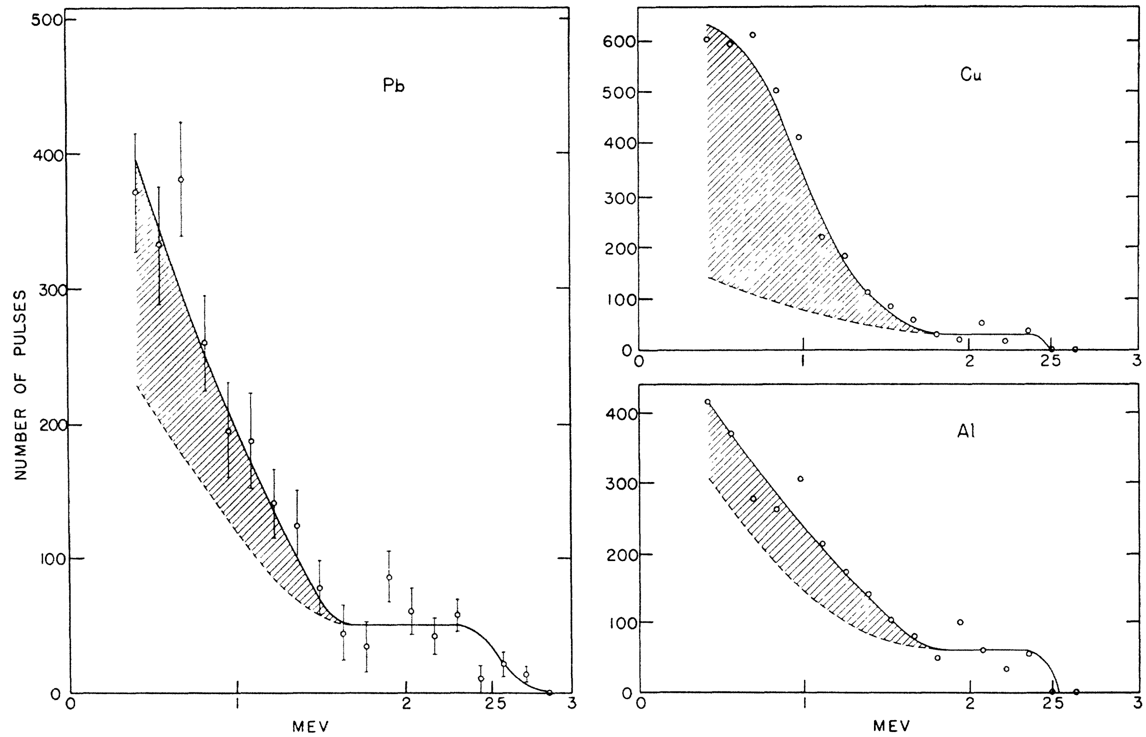

FIG. 3. Distribution in energy of recoiling α-particles knocked on by neutrons which were scattered through 100° by Al, Cu, and Pb. The cross-hatched areas are a measure of inelastic scattering.

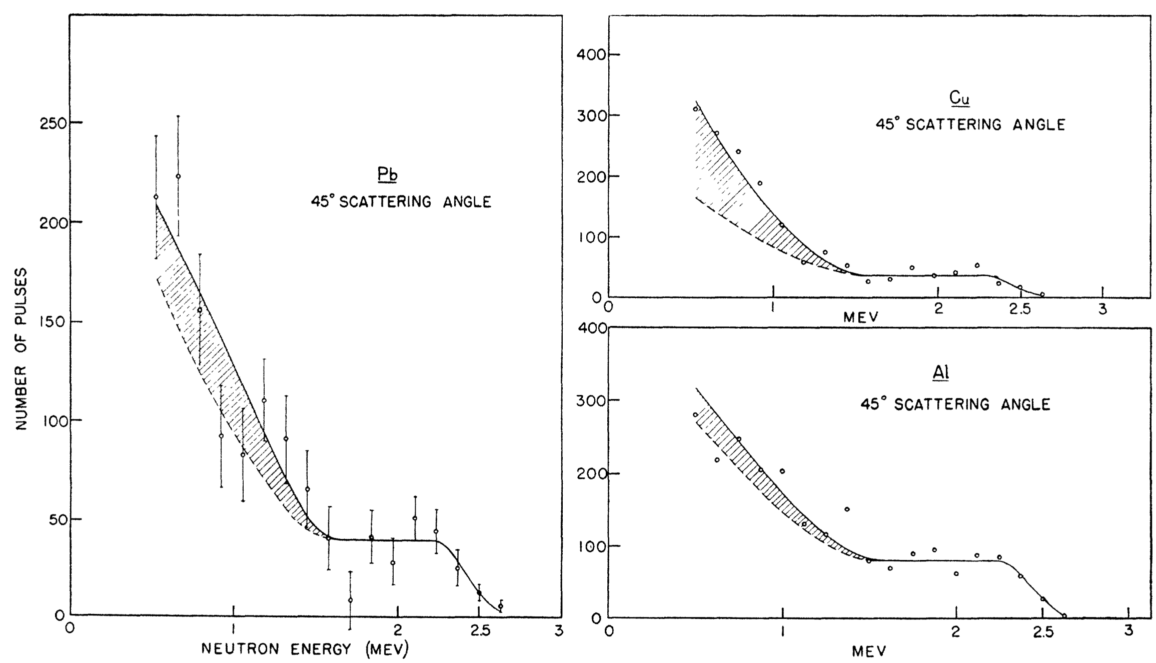

FIG. 4. Distribution in energy of recoiling α-particles from neutrons which were scattered through 45° by Al, Cu, and Pb.

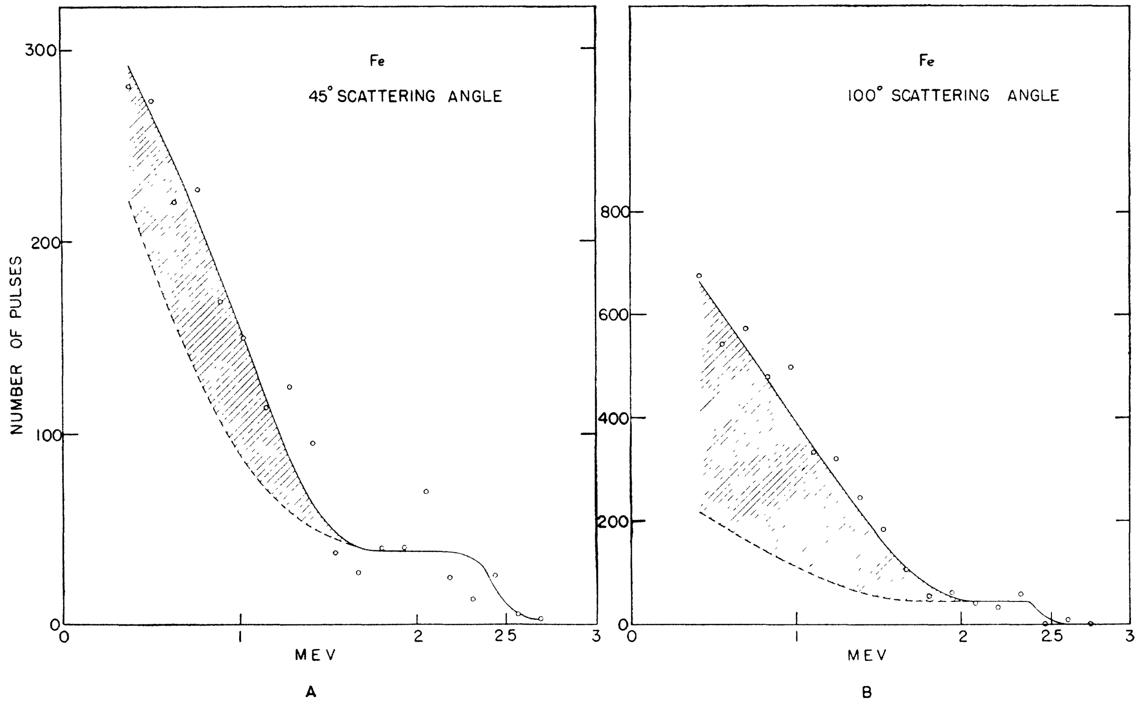

FIG. 5. Distribution in energy of recoiling α-particles from neutrons scattered by Fe through (A) 45° and (B) 100°.

V_2 being the volume of the chamber, r_1 the distance between the scatterer and the target, R the distance between the chamber and the target.

In this calculation it is assumed that the elastically scattered neutrons have the same energy and therefore the same scattering cross section σ_{He} as the primary neutrons, although a fraction ϵ of the original energy is lost even in an elastic collision. The corresponding change of σ_{He} can be neglected for our measurements,[15] but a correction has to be applied because the distribution in energy of the α-particles extends to different energies for the direct and the scattered neutrons. As can be shown easily the cross section should therefore be increased by $100\cdot\epsilon(E_m-\Delta E)/\Delta E$ percent, ΔE being the interval of recoil energy used in the experiment and E_m the maximum energy of an α-particle knocked on by a direct neutron. This correction holds if $\epsilon E_m/\Delta E$ is small compared to 1 and is therefore not valid for very light nuclei.

[15] H. Staub and H. Tatel, Phys. Rev. **58**, 820 (1940).

III. RESULTS

When the paraffin cone was introduced in the path of the direct neutrons it was found that the number of recoils was reduced to about 9 percent in the range of high recoil energies and to 20 to 25 percent at the low values of recoil energy. A considerable fraction of the recoils which were observed in the presence of the paraffin was due to neutrons which passed through the paraffin with or without loss of energy. This was concluded from the fact that the number of recoils counted was reduced to 6 and 14 percent, respectively, if a longer paraffin block was used instead of the cone. Some of the remaining neutrons may have been produced in places where parts of the deuteron beam hit the walls of the target chamber. Some neutrons may have been scattered by the floor or parts of the apparatus. The large background at low recoil energies is mostly due to the very high sensitivity of the chamber for neutrons of lower energies.

In view of this large background the scatterer had to be large in order to make its effect at all

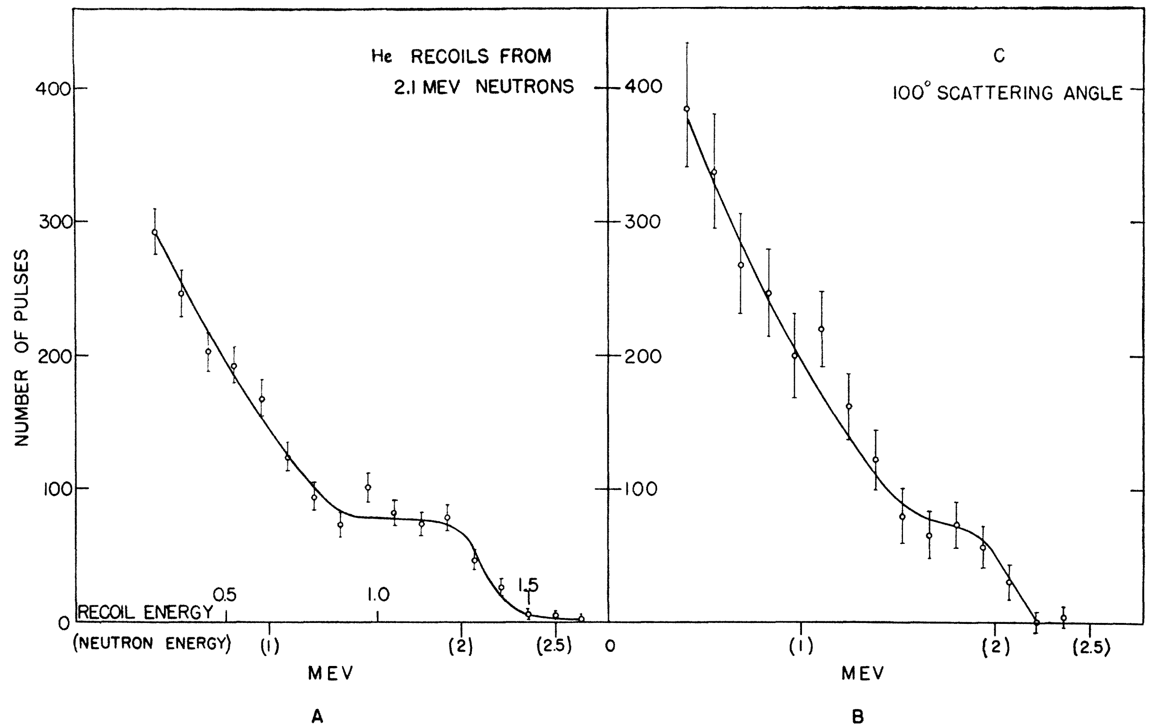

FIG. 6A. Distribution in energy of recoiling α-particles knocked on by 2.1-Mev neutrons from the $d-d$ reaction. B. Distribution in energy of recoiling α-particles from neutrons scattered by carbon through 100°.

observable. But even with a big scatterer the effect was always smaller than the background. Consequently, it was not possible to obtain results with great statistical accuracy although in every measurement more than 10,000 pulses were evaluated. The statistical error given for all the present measurements is the square root of the sum of the numbers, the difference of which is the experimental value.

Measurements of the distribution in energy of recoil α-particles were carried out for scattering angles of 45° and 100° in aluminum, iron, copper and lead, and for 100° in carbon. The results are plotted in Figs. 3, 4, 5, and 6. The circles represent the measured numbers of recoil particles per energy interval. The vertical bars show the statistical errors involved. The energy values given are the energies of neutrons which would produce recoils from zero energy up to the indicated value. For instance "2.5 Mev" corresponds to a recoil energy of 1.6 Mev, and if neutrons of 2.5 Mev are present the distribution curve shows a break at this energy (see Fig. 2).

In order to interpret the curves in Figs. 3, 4, and 5 they should be compared with the distribution obtained for the direct 2.5-Mev neutrons. The latter distribution is reproduced in Fig. 2. It shows an almost flat portion at high recoil energies. All the distributions in recoil energy shown in Figs. 3, 4, and 5 exhibit a similar feature. This indicates that—within the rather large statistical uncertainty—there are no scattered neutrons present of energies between 1.8 and 2.3 Mev. All the neutrons of more than 2.3 Mev will be referred to hereafter as "elastically" scattered neutrons. It should be emphasized, however, that some of these neutrons may have lost energy by inelastic collision, since the resolving power of the apparatus is not sufficient to distinguish neutrons, which have lost less than 10 percent of their energy in an inelastic collision, from those which are elastically scattered. It should be pointed out also that α-particles of less than 300-kev energy were not counted at all so that neutrons which have lost more than about 2 Mev of their energy in inelastic collisions would not have been detected.

Assuming that all the recoils in the flat portion of the curves in Figs. 3, 4, and 5 are due to elastically scattered neutrons one can find the effect of the elastically scattered neutrons at lower recoil energies by extrapolating according to the graph in Fig. 2. The extrapolated distributions are shown by dashed curves in Figs. 3, 4, and 5. The differences between the dashed curves and the experimental curves are measures of the inelastic scattering. The areas corresponding to inelastic scattering are cross-hatched. Figure 3 shows the distribution curves obtained when neutrons were scattered through 100° by Al, Cu, and Pb. In the plot the indicated ordinates give the actually measured numbers. The scales were chosen, however, in such a way that they correspond to equal numbers of nuclei per cm^3 for the three elements. Therefore the ordinates are direct measures of the scattering cross sections. Corresponding plots are given in Fig. 4 for a scattering angle of 45°. Since the geometry is different for different scattering angles the plots in Fig. 3 and Fig. 4 are not directly comparable. The scales of the ordinates in Fig. 4 should be multiplied by a factor of 2.4 to reduce them to the same solid angle as the one at 100°. Figure 5A shows the scattering by Fe at 45°, Fig. 5B at a scattering angle of 100°. In these figures the plots are reduced to the same solid angle. In all cases the cross section for elastic scattering is obviously considerably larger at 45° than at 100°. Furthermore, the figures show differences in the amount of inelastic scattering. The inelastic scattering is very much greater compared with the elastic scattering in Fe and Cu than in Al and Pb. If one measures the cross-hatched areas for any one element at the two scattering angles one finds that they agree within 15 percent when reduced to the same solid angle. In spite of the fact that these areas are obtained as second differences of quantities involving considerable statistical uncertainties, one may conclude that within the accuracy of these experiments the amount of inelastic scattering does not differ appreciably for the scattering angles of 45° and 100°. Thus, our experiments show that the elastic scattering is anisotropic and the inelastic scattering isotropic within the accuracy of our measurements.

In the case of the scattering of neutrons by carbon through 100° the energy loss of a neutron even in an elastic collision is quite appreciable (17 percent). The distribution in energy of the recoil α-particles from neutrons scattered by carbon should therefore be compared with that due to neutrons of about 2.1 Mev energy. Such neutrons were obtained from the $d-d$ reaction by placing the ionization chamber above the target, i.e., by observing in the backward direction. A distribution curve of this kind is shown in Fig. 6A. In Fig. 6B the results for neutrons scattered by carbon are plotted. The breaks in the two curves occur roughly at the same energy so that one can assume that the distribution in energy of the fastest neutrons is about the same in the two cases. Although the distribution curve of the recoils due to neutrons scattered by carbon rises somewhat faster towards lower recoil energies than the curve due to the direct neutrons, the difference is not outside the statistical uncertainty. The experiments do not show any inelastic scattering of 2.5-Mev neutrons in carbon. A comparison of Figs. 6A and B shows once more the difficulty in obtaining good statistical accuracy in these scattering experiments even if large numbers of pulses are counted.

In order to obtain a somewhat better statistical accuracy for the determination of the elastic scattering cross section, experiments were carried out in which only the pulses above 1.1-Mev recoil energy were counted. The method used is described in the second section of this paper. The results of these experiments are given in the second and third columns of Table I. The values are averages both of the results obtained from the photographic records and of those obtained by counting directly, except in the case of Zn, where no records were photo-

TABLE I. Data on scattering cross section $4\pi\sigma(\vartheta)\times 10^{24}$ cm².

1 Element	2 Elastic scattering (B and L) $\vartheta=100°\pm20°$	3 45°±10°	4 Total scattering (Kikuchi *et al.*) 100°	5 45°	Total cross section from transmission experiments
6 C	1.2 ±0.2	—	—	2.0±0.2	1.6±0.3
13 Al	1.1 ±0.2	3.4±0.5	(2.5)	3.8±0.2	2.4±0.3
26 Fe	0.60±0.15	1.7±0.3	2.0±0.4	4.3±0.3	3.1±0.3
29 Cu	0.38±0.1	1.4±0.3	—	3.5±0.3	2.7±0.3
30 Zn	0.68±0.2	1.7±0.3	—	—	3.0±0.3
82 Pb	2.5 ±0.4	5.0±0.6	3.1±0.8	9.2±0.6	6.0±0.7

graphed, and in the case of carbon where only the records were used. The error given is the statistical uncertainty.

According to whether one computes the mean free path from the elastic or the total cross section, one obtains values greater or less than the dimensions of the scatterer. An experiment was carried out therefore with a Pb scatterer which had half the thickness of the scatterer used before. The measurement gave the same value for the elastic scattering cross section which was obtained with the thicker scatterer.

One may object that some of the neutrons scattered by the scatterer and detected in the chamber did not come direct from the target but were scattered by the paraffin. This point was investigated by removing the scatterer and placing the paraffin in such a position that both the direct neutrons and those scattered by the paraffin could reach the chamber. With this arrangement it is possible to measure the distribution in energy of the neutrons which reach the scatterer in the main experiments. No change in the shape of the distribution curve with and without the paraffin could be detected.

IV. DISCUSSION

Columns 2 and 3 of Table I show definitely that for all nuclei investigated the cross section for elastic scattering is appreciably larger for a scattering angle of 45° than for 100°. This is in agreement with the wave mechanical picture of the collision of neutrons with nuclei.[16] A quantitative comparison of the present experiments with a more detailed theory[17] is not possible, as the theory applies only to neutrons of such high energy that the de Broglie wave-length is small compared with the nuclear radius. (For 2.5-Mev neutrons $\lambda/2\pi = 2.9\times 10^{-13}$ cm.)

The anisotropy of the scattering of neutrons was established experimentally for the first time by Kikuchi, Aoki, and Wakatuki[8] (see columns 4 and 5 of Table I), but their experiments do not enable one to distinguish between elastic and inelastic scattering. These authors measured the total ionization due to hydrogen and carbon nuclei knocked on by $d-d$ neutrons which were scattered in different materials. Both the scattering cross section of the gas in the chamber and the ionization produced by the recoiling particles depend on the energy of the neutrons. Only if these effects just canceled, would the results be independent of the energy of the neutrons and give the total scattering cross sections of the materials investigated. Therefore it is not possible to draw definite conclusions from the comparison of their results with ours. If one takes the difference between the two results at 100° (column 4 and column 2 of Table I), one finds that the ratio of inelastic to elastic scattering is much larger for Fe than for Al and Pb. For a scattering angle of 45° this conclusion is not quite so definite since the elastic scattering increases so much for smaller scattering angles.[18]

Above we drew the conclusion that Fe and Cu show relatively more inelastic scattering than Al and Pb already directly from the distribution in energy of the recoiling α-particles. This result agrees also with the measurements of Aoki[5] and of Nonaka[6] who investigated the secondary γ-rays due to excitation of nuclei by $d-d$ neutrons. For obtaining relative values of the inelastic scattering at two angles we believe that the cross-hatched areas in the figures give the most reliable results, while for estimates of the absolute value of the inelastic scattering one has to take differences in Table I.*

It is a pleasure to thank Dr. C. C. Van Voorhis for his cooperation throughout the experiments. We wish also to express our appreciation to Mr. W. A. Hane and Mr. R. L. Kramer for their help in evaluating some of the photographic records.

[16] I. I. Rabi, Phys. Rev. **43**, 838 (1933).

[17] N. Bohr, R. Peierls, and G. Placzek, Proc. Copenhagen Academy, to appear shortly; G. Placzek and H. A. Bethe, Phys. Rev. **57**, 1075 (1940).

[18] From the difference in the cross sections for Pb in columns 5 and 3 it would appear that the inelastic scattering by Pb is much larger at 45° than at 100°, but this is not in agreement with our direct measurements.

* *Note Added in Proof* (*January 8, 1942*).—In the meantime a paper of Dunlap and Little on the scattering of $d-d$ neutrons by lead has appeared (Phys. Rev. **60**, 639 (1941). Their somewhat indirect conclusion that the anisotropic distribution of scattered neutrons is due to elastic scattering is corroborated by our experiments. Also their relatively small value of the cross section for inelastic scattering of the $d-d$ neutrons by lead agrees with our results.