One may also evaluate the term (c), the effect of which is apparent in nuclei containing an odd neutron and an odd proton such as B^{10}. The disintegration energy of C^{10} we observed to be 4.38 Mev. The terms (a) and (b) account, however, for only 2.01 Mev. One deduces therefore, that the extra binding energy in B^{10} due to a term of type (c) amounts to 2.37 Mev.

In Fig. 4 is shown graphically the relative masses of the isobars at mass numbers 10 and 11.

The half-life and beta-ray energy found for C^{10} may be interpreted[11] to mean that transitions between the even-even and odd-odd isobars are of the "allowed" type. In some other cases (e.g., for Na^{22} and P^{30}) this does not, however, seem to be true.

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On the Angular Distribution of Fast Neutrons Scattered by Hydrogen, Deuterium and Helium

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The angular distribution of *d–d* neutrons scattered by hydrogen, deuterium and helium was measured by observing the distribution in energy of the recoil particles in an ionization chamber. The scattering in hydrogen and deuterium was found to be essentially isotropic in the angular interval investigated. In helium, collisions with small energy transfer were more frequent than large angle scattering. The absolute differential scattering cross section of helium was measured.

I. Introduction

MEASUREMENTS of the energy of fast neutrons or the angular distribution of scattered neutrons have in the past been carried out principally in the cloud chamber. This method is the most direct and accurate; however, the evaluation of the experiments is tedious if good statistical accuracy is required.

In the present experiments an attempt is made to measure distributions both in angle and in energy in an ionization chamber by recording the energy of the recoil particles produced in the chamber. The use of an ionization chamber for energy measurements was first proposed by Baldinger, Huber and Staub.[1] These authors derived a simple formula which enables one to obtain the distribution in energy, $S(E)$, of the primary neutrons from the energy distribution $H(E)$ of the recoil particles. For the case in which the scattering is isotropic in the center of mass system and the whole range of the recoil particles is contained in the chamber they show that

$$S(E) = -\frac{1}{n\cdot\sigma(E)\cdot d} E \frac{dH}{dE}, \tag{1}$$

where $\sigma(E)$ is the scattering cross section of the gas in the chamber, n the number of gas atoms/cm^3, d the depth of the chamber. Their experiments were carried out in a chamber filled with He. After the experiments of Staub and Stephens[2] had shown that $\sigma(E)$ for He is strongly dependent on energy around 1 Mev it seemed preferable to use hydrogen for such experiments.

With hydrogen, one is confronted with the difficulty that the recoil protons from fast neutrons have very long ranges. Since the experiments have to be carried out in such a way that the range of the recoils is small compared with all dimensions of the chamber, it is necessary to use very high pressures for measurements in hydrogen in order to reduce the range. Energy measurements in an ionization chamber filled

[1] E. Baldinger, P. Huber and H. Staub, Helv. Phys. Acta **11**, 245 (1938).

[2] H. Staub and W. E. Stephens, Phys. Rev. **55**, 131 (1939).

with gas at high pressure are difficult because of the very high fields necessary to obtain saturation and sufficiently short collecting times. For the present experiments a special ionization chamber was constructed which makes possible the application of high fields over large volumes.

An ionization chamber can also be used for the measurement of angular distributions. If $\sum(\vartheta)$ is the cross section per unit solid angle for scattering into the angular interval between ϑ and $\vartheta+d\vartheta$ in the center of gravity system, the number scattered into this interval is proportional to $2\pi \sin \vartheta \sum(\vartheta)d\vartheta/4\pi$. From conservation of energy and momentum it follows that $\cos \vartheta=(E_{\max}-2E)/E_{\max}$, where E is the energy of the recoil particle in the room system and $E_{\max}$ the maximum energy the recoil particle can obtain in the room system. Therefore

$$\tfrac{1}{2}\sin \vartheta \sum(\vartheta)d\vartheta=-\tfrac{1}{2}\sum(\vartheta)d(\cos \vartheta)=\sum(\vartheta)dE/E_{\max},$$

which is proportional to $H(E)dE$, $H(E)$ being the measured energy distribution. $E_{\max}$ is related to the energy E_0 of the impinging neutron by

$$E_{\max}=\frac{4M_n\cdot M_r\cdot E_0}{(M_n+M_r)^2},$$

M_n being the neutron mass and M_r the mass of the recoiling nucleus. If mono-energetic neutrons are used the distribution in energy of the recoil particles therefore gives a direct measure of the angular distribution of the scattered neutrons in the center of mass system.

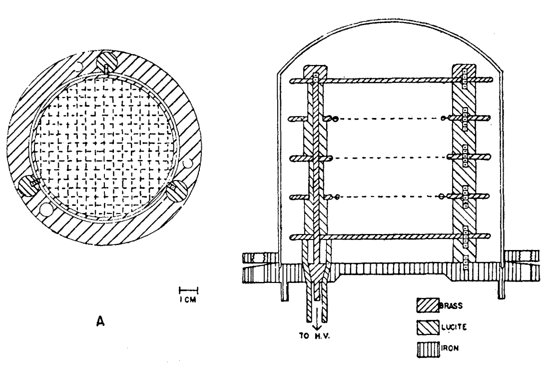

FIG. 1. A. Collecting electrode of the ionization chamber. B. Schematic diagram of the inside of the ionization chamber.

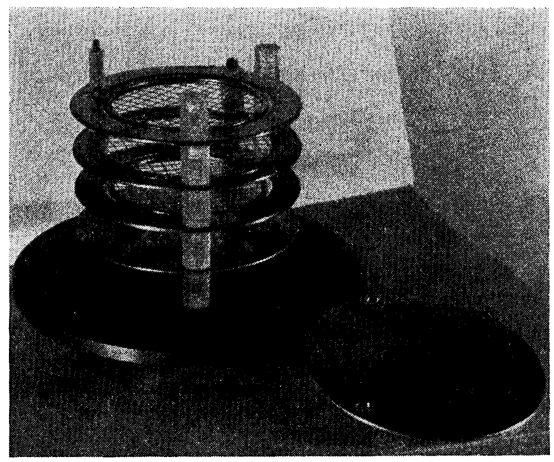

FIG. 2. Photograph of the inside of the ionization chamber.

II. Experimental

The $d-d$ reaction was used as a neutron source. The $d-d$ neutrons emitted at 90° with respect to the deuteron beam are mono-energetic as confirmed recently by Hudspeth and Dunlap,[3] and this fact is corroborated by our experiments. The deuterons were accelerated by the voltage supplied by the transformer-rectifier set in this laboratory. Voltages between 125 and 210 kv were used. No attempt was made to separate the different sorts of ions in the beam in order to avoid secondary neutron sources which might have been produced by the unused beams striking the tube walls. The target consisted of D_2O ice.

In order to obtain sufficiently high collecting fields in the ionization chamber a method first proposed in principle by Ortner and Stetter[4] was applied. Instead of using only two parallel plates as electrodes several are used, connected alternately to the high voltage supply and to the grid of the first stage of the amplifier. The intermediate electrodes are designed to be as transparent as possible to the charged particles. Ortner and Stetter proposed the use of thin Al foils. Electrodes covered with thin foils, however, are too microphonic if they extend over large areas. After various trials the following arrangement was found to be most satisfactory. Square mesh grids were made out of 0.25-mm fuse wire.

[3] E. Hudspeth and H. Dunlap, Phys. Rev. **57**, 971 (1940).
[4] G. Ortner and G. Stetter, Wien. Ber. **142**, 493 (1933).

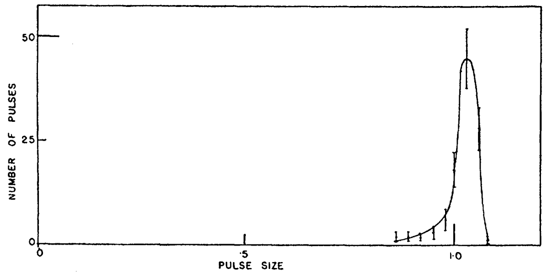

FIG. 3. Distribution in pulse size of 5.3-Mev α-particles in a H_2-Kr mixture.

The wires were six mm apart. At every intersection two perpendicular wires were fixed together by a drop of shellac. Each grid was then clamped between two brass rings. If a grid was used as a collecting electrode, the rings were fixed to Lucite insulators mounted in the guard ring which surrounded them as shown in Fig. 1A. This kind of electrode is relatively nonmicrophonic, and its transparency for perpendicular incidence was measured optically to be 92 percent.

Figure 2 shows a photograph of the inside of the chamber. A schematic diagram is given in Fig. 1B. Five electrodes were used. The first and last ones consisted of plates one mm thick; the three intermediate electrodes were grids of fuse wire. The inner diameter of the rings was 8 cm; the distance between the two end electrodes was likewise 8 cm. Three columns of insulators supported the electrodes. One of the columns contained in its center the high voltage lead. The high voltage electrodes touched this lead. The guard rings of the collecting electrodes were insulated from the high voltage lead by Lucite sleeves which slipped through holes in the guard rings. The connections to the grid of the first stage were made by a lead not shown in Fig. 1. This lead, which was surrounded by a grounded shield, passed between the side wall of the chamber and the electrodes. The walls and the top of the chamber were made of 1.2-mm iron. The whole chamber was suspended by springs from a square frame. The first amplifier tube was contained in a compartment behind the chamber. The collecting voltage was supplied by a 10,000-volt transformer-rectifier circuit with three RC filter stages. For most of the experiments a collecting voltage of 7500 volts was used, producing 3750 volts/cm over a depth of 8 cm.

The ionization pulses were amplified by a 7-stage amplifier with strong inverse feedback and were recorded by means of a torsion type oscillograph[5] on recording paper. The linearity and calibration of the outfit were tested with the aid of artificial pulses of variable size. The pulse generator was described by us previously.[6] A full calibration was photographed at both ends of each record and pulses of one size were recorded at intervals during each run. Both amplifier and oscillograph were found to be linear.

Experiments were carried out in the following three gas mixtures: 5 atmos. Kr+4 atmos. H_2, 5 atmos. Kr+4 atmos. D_2, 7 atmos. He. Krypton is added in order to reduce the range of the recoil protons and deuterons. The maximum range of the H recoils from 25-Mev neutrons was 1.2 cm, that of the D and He recoils smaller.

In order to check the performance of the instrument a very thin source of Po was put into the chamber and fixed to the inside of the top collecting plate. This source emitted 5.3-Mev α-particles in all directions. A study of the α-particle ionization pulses enables one to find out whether the pulse size depends in any way on the direction of the ionization column with respect to the collecting field.

The energy distribution of the Po α-particles was measured in the $Kr-H_2$ mixture and in He. The number energy curves for the two series of experiments are shown in Fig. 3 and Fig. 4. It can be seen from the curves that the peak is sharper in He than in the $Kr-H_2$ mixture. This

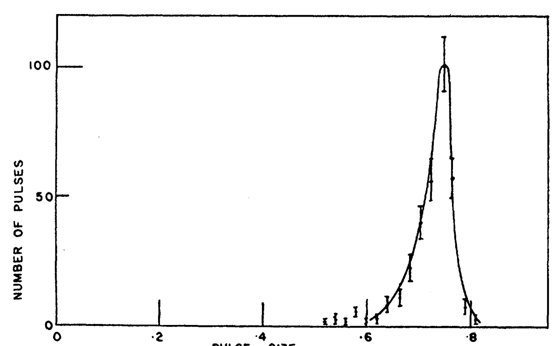

FIG. 4. Distribution in pulse size of 5.3-Mev α-particles in helium.

[5] J. R. Dunning, Rev. Sci. Inst. 5, 387 (1934).

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

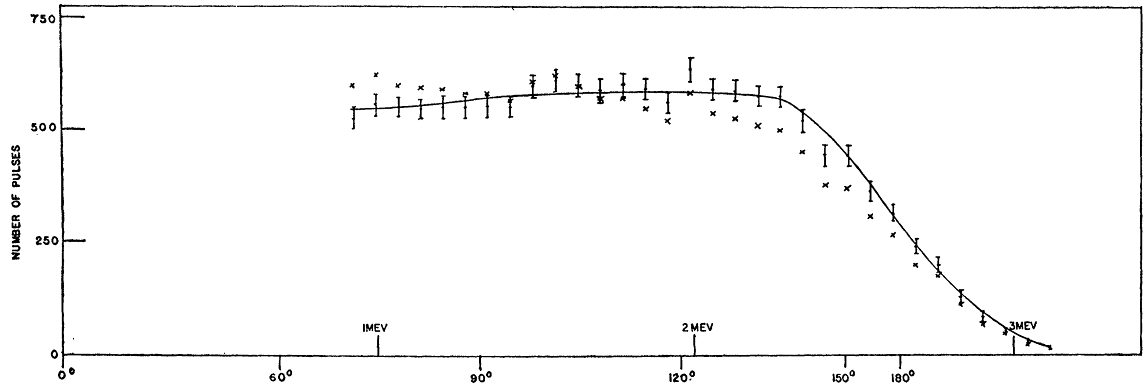

FIG. 5. Distribution in energy of recoil protons. Crosses indicate measured points, bars points corrected for wall effect.

is attributable to the fact that in spite of the high collecting field the collection of the ions in 5 atmos. of Kr is so slow that it is difficult to transmit the pulses through the amplifier without deforming them slightly. In order to obtain good wave forms at the output of the amplifier it had been necessary to increase all time constants to 1/50 sec. or longer. Another drawback to the use of Kr at high pressure is the fact that single fast electrons traversing the large collecting volume produce enough ionization in the chamber to make pulses of appreciable size. This set a lower limit on all energy measurements in Kr, as the pulses produced by electrons could not be distinguished from those produced by low energy recoils. The γ-ray background in the laboratory was sufficient to produce a number of pulses made by electrons comparable with that due to recoils. In evaluating the records care was taken to measure only those pulses which were clearly separated from each other.

The effect of recoil protons from the insulators was tested by taking a run in Kr alone. The number of pulses other than those due to electrons was found to be quite negligible compared to the number of recoils observed with H_2 added.

III. Results

The number energy curve for the $Kr-H_2$ mixture is shown in Fig. 5. The measurement was made at 90° with respect to the deuteron beam (neutron energy 2.53 Mev) at a distance of 45 cm from the target. The crosses represent the measured number of recoils per energy interval at the indicated energies. The scattering angle in the center of mass system is also indicated on the axis of abscissae. The measured numbers were corrected for various edge effects which affect mostly the long range particles and make their pulses appear smaller. Recoils entering the effective volume after starting beyond the edges of the collecting electrodes were also corrected for. For these corrections the range was assumed to be proportional to the $\frac{3}{2}$ power of the energy and as a first approximation the angular distribution was assumed to be isotropic. The corrected points with their statistical errors are plotted in the figure. The large width of the break at the high energy end is probably mostly due to the fact that the transmission through the amplifier is not entirely frequency independent for the very slow pulses. The curve appears essentially flat except for a slight decrease toward lower energies. This decrease appears, however, only after the application of the rather uncertain edge corrections and is not entirely outside the experimental uncertainty which exists in addition to the statistical uncertainty. It is estimated that variations of the cross section as a function of angle could be detected unambiguously only if they were larger than 10 percent and varied slowly with angle.

Figure 6 shows the analogous plot for the case in which the H_2 was replaced by D_2.[7] In this case no deviation from the isotropic scattering law could be detected in the range of angles under investigation. As the deuterium recoils have a

[7] We wish to express our gratitude to Mr. T. Mariner for a mass-spectrographic analysis of the deuterium which had been used in these experiments. The deuterium was found to contain only 2 percent light hydrogen.

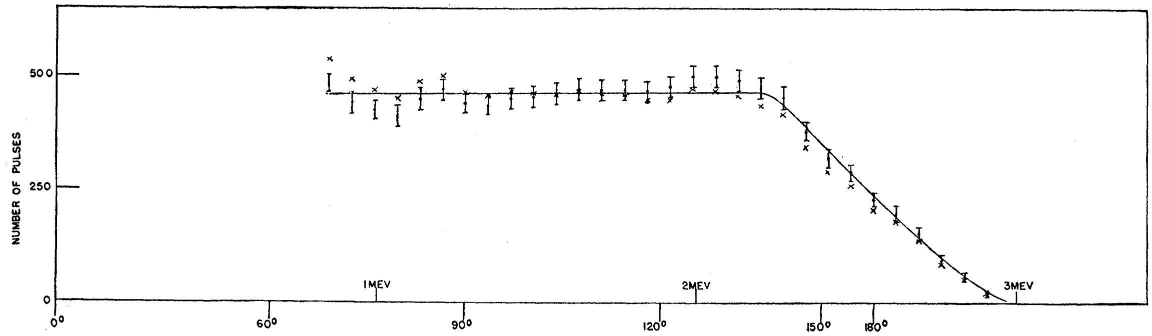

FIG. 6. Distribution in energy of recoil deuterons.

smaller range than the protons, the wall correction is less important.

It follows from Eq. (1) that if 1-Mev neutrons were present[8] the distribution curve would show a break at the corresponding energy of recoil. The height of the rise at this break would be five times greater than that which would be produced by an equal number of 2.5-Mev neutrons as in formula (1) E is smaller by a factor of 2.5 at 1 Mev and $\sigma(E)$ larger by a factor of about 2. The distribution curves in H and D thus seem to indicate that a low energy neutron group is not present with an intensity of more than 3 percent of the main group in agreement with the results of Hudspeth and Dunlap.

Further measurements were made in He. These measurements can be expected to be more accurate than the previous ones as the collecting times are much shorter and no disturbances are produced by fast electrons. The distribution curve obtained is shown in the lower part of Fig. 7. No correction for the edge effect was applied to the measured points as this correction could be calculated conveniently only for an approximately isotropic distribution. The correction would have been small for the He recoils since in the worst case at least 12 ranges are contained in the chamber compared to 7 ranges in the case of hydrogen.

The fact that the distribution curve is almost flat in the high energy region and then rises raised the suspicion that the rise might be due to inelastically scattered neutrons having the energy corresponding to the resonance level in He^5, especially since recent experiments of Staub and Tatel[9] have shown that the resonance reaches up to neutron energies of 1.5 Mev. Neutrons might have been scattered inelastically (1) by various parts of the apparatus in such a way that they would not go directly from the target to the chamber, (2) in the target chamber, (3) in the walls of the ionization chamber.

To test these possibilities the following check experiments were carried out: (1) A cylindrical block of paraffin of diameter somewhat larger than that of the chamber was placed between the target and the chamber in order to absorb neutrons coming directly from the target and give a measure of the number of neutrons which came indirectly. The measurement was made under conditions otherwise exactly the same as those for the previous measurement. The distribution curve showed that the proportion of neutrons which did not come directly from the target was less than 10 percent and that of these neutrons less than half had suffered an energy loss before entering the chamber. (2) To exclude the possibility of inelastic scattering in the liquid air used for cooling the target some experiments were carried out with an air-cooled target of heavy paraffin. No change in the distribution curve could be observed with this arrangement. (3) Neutrons which might have been scattered inelastically in the walls or the iron base plate of the chamber in the absence of the paraffin shield would not have been observed when the paraffin was interposed. The chamber was accordingly surrounded with 20 kg of iron, this being more than five times the total mass of the chamber. The iron consisted of two blocks which had a

[8] T. W. Bonner, Nature **143**, 681 (1939).

[9] H. Staub and H. Tatel, Phys. Rev. **57**, 936 (1940).

cross section of about 70 cm^2. One of them was placed next to the chamber wall on each side, and about 1 cm from it. Within the rather large statistical uncertainty of this experiment (10 percent) no change in the distribution curve could be noticed when the scatterer was introduced. In a further experiment most of the direct neutrons from the target were absorbed by a paraffin cone which was placed in front of the chamber. The recoil distribution thus found was compared with the one obtained when two 5-kg iron scatterers were placed next to the chamber in such a way that the direct neutrons could strike the iron. The additional recoils observed following the introduction of the iron scatterer amounted to less than 10 percent of the number which would have been observed if the direct neutron beam had been allowed to fall on the chamber. As the scatterer had $2\frac{1}{2}$ times the mass of the chamber and subtended about the same solid angle at the center of the collecting volume as the base plate of the chamber, it follows that the effect of the neutrons scattered by the chamber and measured in He was of the order of 5 percent.

If the rise of the distribution curve at low energies (Fig. 7) were due to neutrons of an energy corresponding to the resonance level in He^5, one would expect its position on a number-energy plot to be independent of the neutron energy. For this reason the chamber was also placed below the target where the neutrons have an energy of 3.1 Mev when 210-kv deuterons are used. The distribution curve found using 3.1-Mev neutrons is shown in the upper part of Fig. 7. A definite shift of the rise towards higher energies occurs. In the two parts of Fig. 7 different energy scales, but the same angle scale, were used. It appears that the rise occurs roughly at the same scattering angle in both cases.

All these experiments lead one to the conclusion that the observed distribution is actually due at least in large part to an anisotropy in the neutron-helium sacttering. It is interesting that Baldinger, Huber and Staub[1] found a distribution curve very similar to ours (compare the circles in Fig. 7), although in their case there were probably more slow neutrons present than in ours.

IV. The Absolute Scattering Cross Section of Helium

In view of a possible comparison with theory of the present results on the angular distribution of the scattered neutrons, it seemed desirable to measure the absolute differential scattering cross section, which is defined as the scattering cross section per unit interval of recoil energy.

Both the neutron and the proton yield of the $d-d$ reaction at 90° with respect to the beam are known[10] and the ratio of these yields is known to be independent of the deuteron energy.[11] The number of neutrons incident on the chamber was determined by counting the number of protons from the reaction $d(d, p)H^3$ emitted into a known solid angle, using a second ionization chamber. The number of recoils whose energy lies in the region in which the distribution curve (Fig. 7) is flat (i.e., for $\vartheta > 110°$) was compared with the

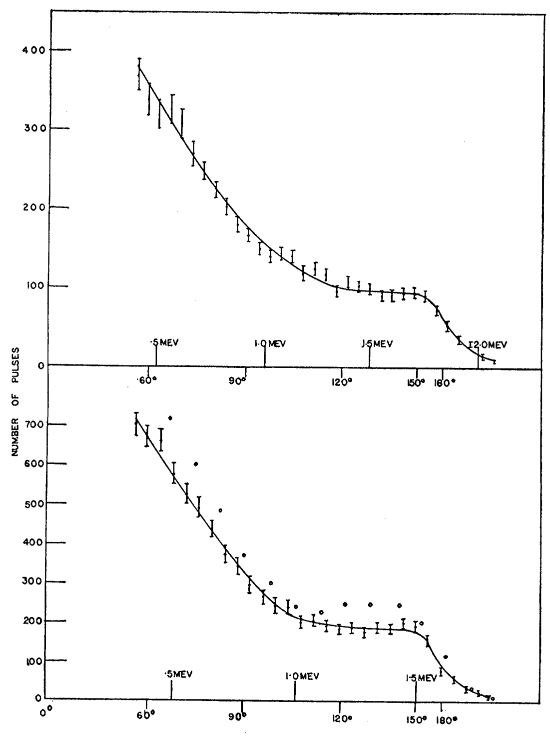

Fig. 7. Distribution in energy of recoil α-particles. Lower curve: distribution due to 2.5-Mev neutrons. Upper curve: distribution due to 3.1-Mev neutrons.

[10] R. Ladenburg and M. H. Kanner, Phys. Rev. **52**, 911 (1937).
[11] R. B. Roberts, Phys. Rev. **51**, 810 (1937).

number of neutrons of 2.5-Mev energy incident on the chamber. This number was calculated from the number of protons counted in the same time interval and from the geometry of the apparatus. As the number of He atoms in the effective chamber volume is known the cross section can be computed.

In the energy interval between 1.1- and 1.6-Mev recoil energy the differential cross section was found to be 9.3×10^{-26} cm^2 per 100-kv recoil energy or

$$E_{\max}\, dQ(E)/dE = 16\times9.3\times10^{-26} = 1.5\times10^{-24}\ \text{cm}^2.$$

This number is corrected for scattered neutrons which do not come directly from the target. The main uncertainty of this result is due to the uncertainty in the value of the absolute neutron yield of the $d-d$ reaction which is estimated to be ±20 percent. The area under the curve for the differential cross section from the highest recoil energies down to the lowest measured values ($\sim$0.35 Mev) is 1.9×10^{-24} cm^2, which is therefore a lower limit to the total cross section for neutrons of 2.5-Mev energy. A more reasonable lower limit of 3.2×10^{-24} cm^2 is found by extrapolating the curve in Fig. 7 horizontally to zero energy.

Staub and Stephens[2] found $\times1.41\pm0.18$ as the ratio of the scattering cross sections of He and H for 2.5-Mev neutrons which gives about 3.1×10^{-24} cm^2 for the absolute value of the He cross section. This result was obtained under the assumption of isotropic scattering, and it should probably be compared with our value for the differential cross section for backward scattering of the neutrons. This discrepancy may be partly due to the fact that in their case only a fraction of the highest energy recoils had their whole range in the chamber. More recent cloud-chamber measurements of Staub[12] which will be published in the near future agree essentially with our value for the helium scattering cross section.

[12] Private communication from Dr. H. Staub.

V. Discussion

The angular distribution of the neutron-proton scattering has been measured by many observers[13] with rather contradictory results. The most reliable measurements are probably those by Dee and Gilbert. These authors find an essentially isotropic distribution in angle over the interval corresponding to our energy measurements. After applying a correction for scattered neutrons Dee and Gilbert find a small deviation from isotropy in the same sense as shown by our corrected values. C. W. Lampson *et al.* and S. Kikuchi *et al.* found a deviation from isotropy in the same direction.

No other experiments on the angular distribution of the neutron-deuteron or neutron-helium scattering have been made.

The fact that no deviation from isotropy could be detected in deuterium in the angular region investigated was unexpected. Measurements of Tuve, Heydenburg and Hafstad[14] showed a very large deviation from Rutherford scattering in the proton-deuteron scattering. A similar deviation from isotropy might have been expected for the scattering of 2.5-Mev neutrons.

The theoretical implications of the scattering of neutrons in helium will be discussed in a separate paper.[15]

VI. Acknowledgments

We wish to express our gratitude to Professor Rudolf Ladenburg for his interest and encouragement and to Professors Louis A. Turner and J. A. Wheeler for much helpful advice.

We are indebted to Dr. I. Brody of the Egyesult Izzo R. T., Hungary, for the gift of 60 liters of krypton.

[13] P. I. Dee and C. W. Gilbert, Proc. Roy. Soc. **A163**, 265 (1937); T. W. Bonner, Phys. Rev. **52**, 685 (1937); F. N. D. Kurie, Phys. Rev. **44**, 463 (1933); L. Meitner and K. Philipp, Zeits. f. Physik **87**, 484 (1934); P. Auger and G. Monod-Herzen, Comptes rendus **196**, 1102 (1933); W. D. Harkins, M. Kamen, H. W. Newson and D. M. Gans, Phys. Rev. **47**, 511 (1935); P. G. Kruger, W. E. Shoupp and F. W. Stallmann, Phys. Rev. **52**, 678 (1937); C. W. Lampson, D. W. Mueller and H. A. Barton, Phys. Rev. **51**, 1021 (1937); S. Kikuchi, H. Aoki and T. Wakatuki, Proc. Phys.-Math. Soc. Japan **21**, 410 (1939).

[14] M. A. Tuve, N. P. Heydenburg and L. R. Hafstad, Phys. Rev. **50**, 806 (1936).

[15] J. A. Wheeler and H. H. Barschall, to be published soon.

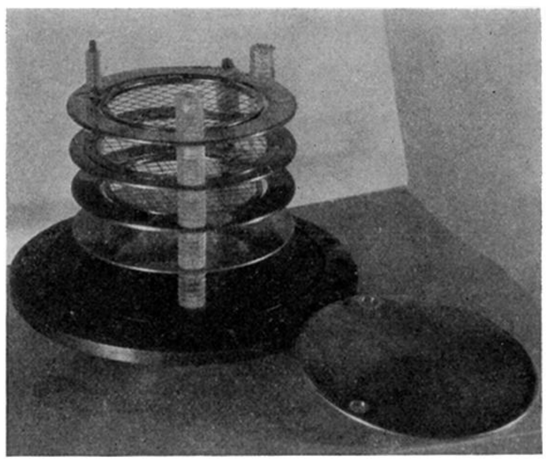

FIG. 2. Photograph of the inside of the ionization chamber.