On the Angular Distribution of Neutrons in the Photo-Disintegration of the Deuteron

GORDON A. R. GRAHAM AND HANS HALBAN, JR
École Libre des Hautes Études, New York, New York

I. INTRODUCTION

WIGNER[1] has shown that the large cross section for the scattering of slow neutrons by protons leads to the assumption that the nucleus of the deuteron has a ^1S level with an energy of the order of 70,000 electron volts,[2] however, the scattering cross section does not depend on the sign of this level.

According to Fermi,[3] the capture of slow neutrons by protons is caused by the transition from a ^1S state to the fundamental ^3S state of the deuteron by the mechanism of magnetic dipole radiation. The sign of the ^1S level may be determined from the value of the capture cross section. It is found that the level is virtual.

Teller[4, 5] has pointed out that a study of the scattering of slow neutrons by ortho- and para-hydrogen will also determine the sign of the ^1S level, and experimental results[6] confirm that the level is virtual.

The photo-disintegration of the deuteron has been discovered by Chadwick and Goldhaber.[7] It has been shown that it can take place by two different processes. The theory of the electric photo-effect—a $^3S-^3P$ transition by electric dipole—has been discussed by Bethe and Peierls,[8] Breit and Condon,[9] and others[10] and most recently by Rarita, Schwinger, and Nye.[11]

Fermi[3] has shown that the inverse process of the magnetic $^1S-^3S$ capture contributes also to the photo-disintegration of the deuteron. This contribution is especially important, if the energy of the γ-rays (or x-rays) lies near the threshold of the photo-effect. The angular distribution of the magnetic photo-neutrons is spherically symmetric. A detailed discussion of most of the above mentioned facts is given by Bethe and Bacher.[12]

The cross section for the magnetic photo-effect is:

$$\sigma_m = \frac{8\pi}{3}\frac{e^2}{\hbar c}\cdot\frac{\hbar^2}{M^2c^2}\cdot\frac{(\mu_p-\mu_n)^2}{4}\cdot\epsilon^{\frac{1}{2}}(\epsilon^{\frac{1}{2}}\mp\epsilon'^{\frac{1}{2}})^2\frac{E^{\frac{1}{2}}}{(E+\epsilon)(E+\epsilon')}, \quad (1)$$

where M is the mass of the neutron, μ_p and μ_n the magnetic moments of proton and neutron, ϵ the binding energy of the deuteron, ϵ' the energy of the singlet state, and $\epsilon+E$ the energy of the disintegrating γ-ray, the minus and plus sign standing according to whether the singlet state of the deuteron is stable or virtual.

Assuming a virtual level at 70,000 ev, $\epsilon = 2.2$ Mev and $\mu_p - \mu_n = 4.7$[13, 14] we find for the 2.62 Mev γ-rays of radiothorium

$$\sigma_m = 3.4\times 10^{-28}\ \text{cm}^2.$$

In principle it is not even necessary to know the magnetic moments of proton and neutron. Once the energy of the ^1S level, ϵ', has been determined, σ_m can be obtained for γ-rays of all energies by

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[3] Fermi, Ricerca Scient. **7**, 2 (1936).
[4] E. Teller, Phys. Rev. **49**, 420 (1936).
[5] J. Schwinger and E. Teller, Phys. Rev. **52**, 286 (1937).
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[8] Bethe and Peierls, Proc. Roy. Soc. **A148**, 146 (1935).
[9] G. Breit and E. U. Condon, Phys. Rev. **49**, 904 (1936).
[10] Massey and Mohr, Proc. Roy. Soc. **A148**, 206 (1935); Mamasachlisoff, Physik. Zeits. Sowjetunion **8**, 206 (1935); Hall, Phys. Rev. **49**, 401 (1936); Fröhlich, Heitler and Kahn, Proc. Roy. Soc. **A174**, 85 (1940); Ma, Proc. Camb. Phil. Soc. **34**, 365 (1938).
[11] Rarita, Schwinger, and Nye, Phys. Rev. **59**, 209 (1941).
[12] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8** (1936).
[13] L. W. Alvarez and F. Bloch, Phys. Rev. **57**, 352 (1940).
[14] Kellogg, Rabi, Ramsey, and Zacharias, Phys. Rev. **55**, 595 (1939).

the simple relation

$$\sigma_m=\frac{\sqrt{2}}{3}Mc^2\cdot E_0^{\frac{1}{2}}\cdot E^{\frac{1}{2}}\frac{(\epsilon'+\frac{1}{2}E_0)}{(\epsilon'+E)}\cdot\frac{1}{(E+\epsilon)(\frac{1}{2}E_0+\epsilon)}\times\sigma_{\text{cap}},\quad (2)$$

where σ_{cap} is the capture cross section of the proton for neutrons of energy E_0 (laboratory system), ϵ again the binding energy of the deuteron, and $E+\epsilon$ the energy of the disintegrating γ-ray. It is interesting to note that (2) does not even contain explicitly the sign of the ^1S level. This equation allows the calculation of σ_m for γ-rays of any energy, provided that σ_{cap} is known for one energy (for instance for thermal neutrons).

The cross section for the electric photo-effect depends on the range and type of the nuclear forces. According to Bethe and Bacher[12]

$$\sigma_{\text{el}}=\frac{8\pi}{3}\cdot\frac{e^2}{\hbar c}\cdot\frac{\hbar^2}{M}\cdot\frac{\epsilon^{\frac{1}{2}}E^{\frac{3}{2}}}{(E+\epsilon)^3}\quad (3)$$

should lead for 2.62 Mev γ-rays to a slight underestimation of the cross section. It gives:

$$\sigma_{\text{el}}=7.6\times10^{-28}\text{ cm}^2.$$

The total cross section for 2.62 Mev γ-rays would therefore be

$$\sigma=\sigma_m+\sigma_{\text{el}}=11\times10^{-28}\text{ cm}^2.$$

This would be in good agreement with the value $(10\pm0.8)\times10^{-28}$ cm^2 found by one of the present authors.[15] It must, however, be pointed out that this experimental value is most likely too low. Experiments which were started in 1939 and had to be discontinued because of the war point to a slightly higher value for the total cross section.

A discussion of the photoelectric effect by Breit and Condon[9] comes to the conclusion that the cross section must in any case be somewhat higher than the value obtained by Bethe and Peierls. The cross section depends on the type and range of nuclear forces but has a minimum value of 15×10^{-28} cm^2 for 2.62 Mev γ-rays. The angular distribution of the neutrons due to the photoelectric effect is, according to all these authors, a $\sin^2$ distribution around the direction of the incident γ-ray.

Fröhlich, Heitler, and Kahn[10] have calculated the photoelectric effect on grounds of the meson theory of nuclear forces. They obtain for 2.62 Mev γ-rays a cross section of 12.6×10^{-28} cm^2. Fröhlich, Heitler, and Kahn, as well as Rarita, Schwinger, and Nye,[11] came to the conclusion that the tensor coupling of the vector meson theory modifies the angular distribution of the neutrons produced by the photoelectric effect by the introduction of a spherically symmetric term in addition to a $\sin^2$ term. According to Rarita and his colleagues, it is, however, not possible to predict either the contribution of this symmetric term or the cross section for the photoelectric effect without more knowledge of the nuclear forces.

Several attempts to determine experimentally the relative contribution of the magnetic and electric component to the total cross section of the photo-effect have been made. They are all based upon the assumption that the neutrons produced by the magnetic effect have a spherically symmetric distribution while those due to the electric effect have a $\sin^2$ distribution around the beam of disintegrating γ-rays (or x-rays). We have seen that according to more recent theoretical work this assumption is not necessarily correct.

Chadwick, Feather, and Bretscher[16] studied 65 photo-proton tracks, that had been produced in a cloud chamber by 2.62 Mev γ-rays. The primary object of this work was the determination of the binding energy of the deuteron. The authors found that the angular distribution of the photo-protons can be explained by a $\sin^2$ distribution alone. They pointed out however, that the small number of tracks they have observed does not allow a final conclusion as to the existence of the magnetic photo-effect.

Richardson and Emo[17] who also worked with a cloud chamber came to a similar conclusion. They used, however, harder γ-rays (3 Mev) for which the contribution of the magnetic effect should be of less importance.

[15] H. Halban, Comptes rendus **206**, 1170 (1938).

[16] Chadwick, Feather, and Bretscher, Proc. Roy. Soc. **A163**, 366 (1937).

[17] R. J. Richardson and L. Emo, Phys. Rev. **53**, 234 (1938).

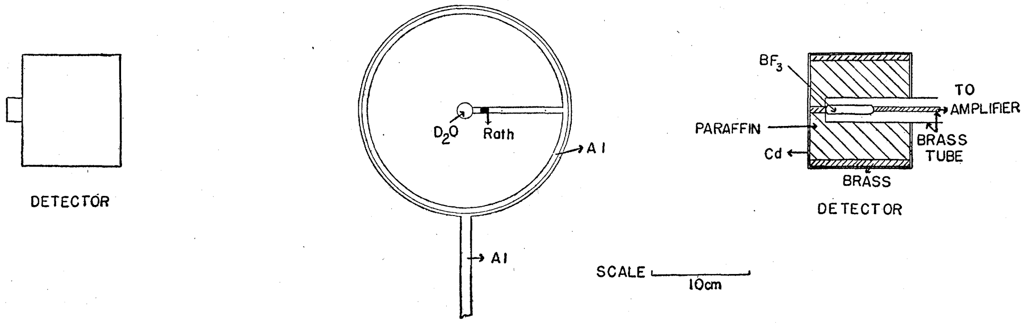

FIG. 1. The notation "Rath" should be chaged to "Rd Th."

Measurements of the angular distribution of photo-neutrons produced by 2.62 Mev γ-rays in a sphere of heavy water (1-cm diameter) have been performed by Halban.[18] The intensity of photo-neutrons observed (per unit solid angle) in the direction of the disintegrating γ-rays was found to be (7 ± 6) percent of the intensity observed at 90°. Allowing for geometrical conditions, an upper limit of only 0.9×10^{-28} cm^2 for the cross section of the magnetic photo-effect was obtained.

More recently, Myers and Van Atta[19] performed a similar experiment with a continuous spectrum of x-rays reaching up to 2.43 Mev. The distribution of the photo-neutrons is found to be predominantly isotropic as should be theoretically expected for energies so near to the threshold of the photo-effect. These authors estimate the cross section averaged over the continuous spectrum to be 10^{-28} cm^2. They point out that this estimate has a low precision.

The measurements of Myers and Van Atta prove the existence of the magnetic photo-effect.[20] The results of Halban are not in direct contradiction to these measurements, since his upper limit for the cross section is comparable to the estimate of Myers and Van Atta. The value of the cross section is, however, in both cases considerably lower than the calculated value. This contradiction is rather serious since the cross section of the magnetic effect—contrary to the electric effect—can be well predicted, once the values of the cross section for the scattering and capture of slow neutrons by protons are known (Eq. (2)). The existence of a spherically symmetrical term in the electrical photo-effect would make the discrepancy at 2.62 Mev and 3 Mev even worse.

In view of the fact that Myers and Van Atta worked with a continuous spectrum which makes an estimation of the cross section very difficult and that considerable progress in technique has been achieved since Halban's measurements were made, it seemed, therefore, desirable to obtain new results with 2.62 Mev γ-rays.

II. EXPERIMENTAL METHOD

Figure 1 shows the experimental set-up. An aluminum ring of 20-cm diameter, 5-mm width and 3-mm thickness could rotate upon a second ring of similar dimensions which was held by a support 80 cm above the floor.

A glass sphere (0.5-mm wall thickness) filled with heavy water was placed in the center of the ring. The radiothorium source (200 mc contained in a platinum cylinder of 3.5-mm diameter and 8-mm length) was placed at a fixed distance, the prolongation of its axis passing through the center of the sphere. The photo-neutrons were detected by two boron chambers which were each placed in a cadmium covered paraffin cylinder of 10-cm diameter and 15-cm length (in the following referred to as detectors). The paraffin cylinders were 75 cm from each other and were placed symmetrically to the heavy water sphere. Variation of the angle between the primary γ-rays and the detected photo-

[18] H. Halban, Nature **141**, 644 (1938).
[19] F. E. Myers and L. C. Van Atta, Phys. Rev. **61**, 19 (1942).
[20] The contribution of the spherically symmetric component is 5/6 of the total effect in their case. This is much more than the meson theory would give under any assumption for the symmetrical term of the electric effect.

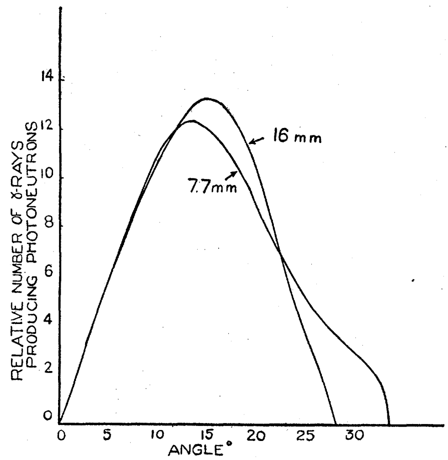

FIG. 2.

neutrons was obtained by rotation of the aluminium ring.

The choice of the geometrical conditions was decided by a number of considerations. It is, of course, desirable to have the angle between the primary γ-rays and the observed photo-neutrons as well defined as possible. Therefore, the solid angle under which the heavy water sphere appears to the source and the solid angle under which the paraffin cylinder appears to the sphere should both be small. Because of the lack of intensity, ideal conditions cannot be obtained. In our arrangement, the neutrons emitted by the sphere and slowed down in the paraffin cylinder are contained in a cone of 7.5° opening. The angular distribution of the γ-rays is given in Fig. 2. It may be seen that this distribution reaches up to 33° (angle between the axis of the radiothorium and the γ-ray producing a photo-neutron).

There are two reasons for choosing a larger solid angle between source and sphere than between sphere and detector. The angular distribution of neutron producing γ-rays can be calculated, since for any given volume element in the sphere the number of neutrons produced is proportional to the flux of γ-radiation. The angular distribution of detected photo-neutrons cannot be calculated. The probability for a neutron reaching a given part of the paraffin cylinder to be slowed down by the paraffin and detected by the boron chamber is a complicated function of the coordinates. It is, therefore, preferable to limit this uncertainty by giving the cone of detected neutrons a very small opening.

The second reason for this choice lies in the fact that the radiothorium source produces a certain amount of neutrons.[21] In order to make the ratio, background neutrons to photo-neutrons, as small as possible, one must again choose a large angle between source and sphere and a small angle between sphere and detector.

Once these two angles have been fixed, one has still the choice of the distance between source and sphere, and between sphere and detector. For a given solid angle the diameter of the paraffin cylinder is proportional to the distance from the sphere. If the cylinder gets too large, neutrons slowed down near its surface will be absorbed before reaching the boron chamber; if it is too small, the slowing down becomes inefficient. An optimum for the size of the cylinder and for the position of the boron chamber in it was found empirically.

For a given opening of the solid angle between source and sphere, the diameter of the sphere is proportional to the distance between sphere and source. The intensity of photo-neutrons will be proportional to the diameter of the sphere. For an ideal experiment one should, however, choose a very small sphere so as to reduce scattering of the photo-neutrons by the heavy water to a minimum. Again a compromise had to be made. Measurements were carried out with two spheres of 7.7- and 16-mm diameter. The distance between the center of the source and the center of the sphere was 10 mm in the first case and 20 mm in the second. The angular distributions (Fig. 2) are, of course, somewhat different. This necessitates a different correction for the two sets of measurements. (See Section IV.)

III. EXPERIMENTAL RESULTS

With the 16-mm sphere measurements were made with the axis of the source forming an angle of 0°, 45°, 90°, 135°, and 180° with the line connecting the heavy water sphere with the left detector. The measurements at 45° and 135°

[21] The origin of this neutron production is not quite clear. It may however most likely be attributed to (α, n) reactions in light elements contained in the source. Comparison of several sources, all contained in platinum cylinders and prepared with special care, gave a constant ratio between γ intensity and neutron intensity.

TABLE I. Counts per minute obtained with the 16-mm sphere.

Left detector						Right detector				
0°	45°	90°	135°	180°		0°	45°	90°	135°	180°
2.60	—	4.08	—	2.26	16-mm sphere	1.89	2.78	3.51	2.71	2.08
1.47	—	1.36	—	1.21	No sphere	0.94	0.99	1.01	1.01	1.07
1.13±.05	—	2.72±.04	—	1.05±.04	Diff.	0.95±.05	1.79±.05	2.50±.04	1.70±.06	1.01±.05

were made in a separate run. For each position readings were taken with both boron chambers (see, however, below and Section IV). In order to account for the background neutrons, measurements had also to be made in absence of the heavy water sphere.

The sensitivity of the detectors was frequently controlled by placing a photo-neutron source (of higher intensity than the small sphere+radiothorium source used for the measurements) symmetrically to the two detectors. The sensitivity of the boron chambers was usually found to be constant within 1 or 2 percent from one day to the other. For about $\frac{2}{3}$ of all measurements, the position was changed every hour, so that a complete set of measurements was obtained two or three times within a day. One third of the measurements was carried out in 8 to 10-hour runs over-night. The over-night measurements agreed well with the shorter runs. A careful survey of the deviations of individual measurements from the average was made. It was usually found that the root mean square deviation was 10 to 20 percent higher than would be expected from mere statistical fluctuations. In view of the very low intensity observed, this is not surprising.

The precision of our geometrical arrangements was better than 1° (alignment by a beam of light) which is certainly more precise than our measurements necessitate.

Table I gives the results obtained with the 16-mm sphere. The intensities are given in counts per minute. The 0° position is the one for which the source is between the heavy water and the left detector. The background of the chambers in the absence of source was 0.15/min.

It can be seen that for the left detector the 0° position gives a higher intensity than the 180° position, while for the right detector, the opposite is the case. This is caused by the scattering of background neutrons from the source by the heavy water sphere. For this reason, only measurements in the 0° position for the left detector and in the 180° position for the right detector were used in the final calculations (see Section IV).

Table II gives the results for the 7.7-mm sphere.

IV. CORRECTIONS

We assume that the angular distribution of the photo-neutrons can be described by

$$I(\theta)\sin\theta d\theta=(a+b\sin^2\theta)\sin\theta d\theta.$$

The ratio of the intensities measured with the same detector at 0° and 90° would then be

$$I_0/I_{90}=a/(a+b).$$

Our experimental conditions necessitate, however, a number of corrections.

Owing to the geometrical conditions as described in Section II, the path of a neutron observed in the 0° (90°) position forms an angle of between 0° and 32° (58° and 90°) with the γ-ray that produced it. In consequence, the intensity in the 0° position is partly owing to

TABLE II. Counts per minute obtained with the 7.7-mm sphere.

Left detector				Right detector		
0°	90°	180°		0°	90°	180°
1.60	2.10	1.45	7.7-mm sphere	1.38	2.08	1.45
1.25	1.21	1.16	No sphere	1.14	1.13	1.11
0.35±.04	0.89±.04	0.29±.04	Diff.	0.24±.04	0.95±.04	0.34±.04

the $\sin^2$ component, and the intensity observed at 90° is too low. The necessary correction can be calculated from the angular distributions of Fig. 2. The correction for the intensity observed in the 0° position is $-0.08\times b$ for the 16-mm sphere and $-0.09\times b$ for the 8-mm sphere. For the 90° position, the corrections are $+0.08\times b$ and $+0.09\times b$. The final opening of the neutron beam has been accounted for in this correction by assuming equal probability of neutron detection for each element of the circular surface of the paraffin cylinder facing the sphere. This assumption is somewhat arbitrary but it leaves an uncertainty of not more than 15 percent of the total amount of the correction.

A further correction is due to the scattering of neutrons by parts of the apparatus and by the walls of the room. The aluminum ring was sufficiently thin and had a sufficiently large diameter to make its contribution to this effect negligible. The influence of one paraffin cylinder upon the other will slightly increase the sensitivity of detection (1–2 percent), but this effect introduces no correction since the detectors are placed symmetrically. The scattering of the room was studied by measuring deviations from the $1/r^2$ law for the neutron intensity observed with the detectors at various distances from a small photo-source. The interpretation of these results leads to the conclusion that only 91 percent of the intensity recorded by the detector is caused by neutrons coming directly from the sphere while 9 percent is caused by neutrons scattered by the surrounding walls.

As far as our measurements are concerned, the scattering of photo-neutrons by the heavy water does not involve a correction of the isotropical component of the photo-effect. It necessitates, however, a considerable correction for the $\sin^2$ component, and it is not easy to estimate its amount. The scattering has a double influence on our observations. It tends to make the angular distribution of the anisotropic component of the photo-neutrons isotropic, and it produces a slowing down of all scattered neutrons. In consequence of the scattering, a fraction of the neutrons which were directed towards the detector will not reach it; on the other hand, some secondary neutrons which have changed their original direction after being scattered—and have in consequence a lower energy[22]—will be detected. The net balance for the neutron *flux* is evident. Since the intensity has a maximum at 90°, the scattering can only reduce the *flux* observed in the 90° position. On the other hand, the number of *counts* recorded by the detector will not decrease to the same degree as the flux; the secondary neutrons scattered from other angles into the 90° position will not be recorded with the same sensitivity as the primary neutrons, since they have a lower energy. Qualitatively, we can say that they will have a higher probability to be detected,[23] but it is impossible to say whether this effect compensates (or even over-compensates) the reduction of counts owing to the decrease of the primary neutron-flux. Scattering by the heavy water will evidently result in an increase of both neutron flux and number of counts for the 0° position. The correct method to determine these corrections would be an extrapolation to radius zero of the number of counts measured with spheres of different radii for both the 0° and 90° position. This is not possible because the finite size of the source would not allow a comparison of geometrical conditions with sufficient precision for such an extrapolation. For an extrapolation of the *ratio* of the intensities observed at 0° and at 90°, the geometry is, however, sufficiently well known.[24] This procedure would be quite correct if the correction would only apply to the intensity observed at 0°. Unfortunately, this is not the case. A certain justification for this procedure lies in the fact that scattering by the heavy water influences

[22] The biggest energy loss will be 8/9 of the primary energy for neutrons which have changed their direction by 180° in a central collision with a deuteron, assuming the probability of two successive collisions for one neutron to be negligible. The spectrum of secondary neutrons will therefore cover all energies above 1/9 of the primary energy.

[23] We have for instance observed that the detectors record 200,000 ev neutrons (Ra Th γ D) with 1.5 times higher probability than 900,000 ev neutrons (Ra Th γ Be).

[24] In this case the distribution of radiothorium inside the source must be known only for the calculation of the angular distributions given in Fig. 2 and for the corrections deducted from them. The assumption of a homogeneous distribution—which we made, and which seems reasonable in view of the care with which the source was prepared—may involve a small mistake in this correction. In the case of extrapolating intensities and not ratios of intensities any inhomogeneity of the source would lead to considerable mistakes.

the number of counts recorded much more in the 0° position than in the 90° position.[25]

The effects upon the angular distribution discussed so far have all three the tendency to make the intensity for the 0° position too large. Only the scattering of photo-neutrons by the radiothorium source has the opposite effect. This effect is, furthermore, relatively larger for the 8-mm sphere than for the 16-mm sphere. It can be roughly estimated to reduce the 0° intensity by about 5 percent for the 8-mm sphere and 2 percent for the 16-mm sphere.

Correcting the results of Table I and Table II, respectively, for geometry and scattering, one obtains for the 16-mm sphere

$$(a/b)_{16}=0.42\pm0.03,$$

and for the 8-mm sphere

$$(a/b)_8=0.34\pm0.04.$$

Extrapolating a/b to zero radius gives

$$(a/b)_0=0.26\pm0.08.$$

The intensities obtained at 45° and 135° are, within our precision, equal. The correction for room scattering is the same as for the 0° and 90° positions. No correction for scattering of photo-neutrons by the source is needed. The correction for angular distribution of the primary γ-rays is zero because of the symmetry of the $\sin^2$ curve at 45°. The intensities obtained with the 16-mm sphere after application of all corrections except the one for scattering by the heavy water have been applied are:

$$I_{90}=2.52,\quad I_{135}^{45}=1.54,\quad I_0=0.75.$$

Qualitatively, it can be understood that scattering by the heavy water tends to make $b/2>(I_{90}-I_{45})>(I_{45}-I_0)$.

Under ideal conditions these differences would be both equal to $b/2$. We can also say $I_{45}>a+b/2$, and, therefore,

$$\frac{2I_{45}-I_{90}}{2(I_{90}-I_{45})}>\frac{a}{b}.$$

This gives $a/b<0.29$, an upper limit for a/b, which indicates that the value $(a/b)_0=0.26\pm0.08$, found above by extrapolation, might be too high within the limits of our precision.

V. DISCUSSION

The extrapolated value $(a/b)=0.26$ leads to a cross section

$$\sigma_a=\frac{a}{a+\frac{2}{3}b}\cdot\sigma_{\text{total}}=(3.9\pm0.12)\times10^{-28}\ \text{cm}^2$$

for the spherically symmetrical component of the photo-effect if we use 10×10^{-28} cm^2 for the total cross section. This has to be compared with $\sigma_m=3.4\times10^{-28}$ cm^2, the cross section calculated for the magnetic photo-effect (by putting into (2) the capture cross section[26] for thermal neutrons $\sigma_{\text{cap}}=3.1\times10^{-25}$ cm^2 and 70,000 ev, for the energy of the virtual ^1S level). The agreement is satisfactory and would—within our low precision—remain satisfactory if the total cross section for the photo-effect should be somewhat higher. A considerably higher precision would be needed in order to obtain any information on the existence of a spherically symmetrical term of the electric photo-effect. It might then be reasonable to argue that the cross section for the magnetic effect can be predicted sufficiently well to attribute any excess of σ_a above the calculated σ_m to the symmetrical component of the electric photo-effect. Measurements at different energies are, however, highly desirable, especially at higher energies, where σ_m decreases while the symmetrical part of the electric photo-effect should increase.

The cross section for the $\sin^2$ component of the photo-effect is according to our results

$$\sigma_b=\frac{\frac{2}{3}b}{a+\frac{2}{3}b}\times\sigma_{\text{total}}$$

with $\sigma_{\text{total}}=10^{-27}$ cm^2, $\sigma_b=7.2\times10^{-28}$ cm^2.

It is our intention to resume these measurements with hydrogen filled ionization chambers as neutron detectors. This will make it possible to reduce the effect of neutron scattering in the heavy water, if only recoil protons of longest range are recorded.

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[25] The absolute change of the neutron *flux* is of the same order (but opposite sign) for the two positions. The relative change is therefore several times bigger for the 0° position (see final values of a and b). The effect of slowing down upon the neutron *counts* tends to increase this difference.

[26] Schultz and Goldhaber, Phys. Rev. **67**, 202 (1945).

We want to thank Mr. N. Veall for the preparation of the boron chambers and Mr. D. M. Eisen for his efficient help with the measurements.

SUMMARY

200 mc of Ra Th are placed near a small sphere of heavy water. The relative intensity of the photo-neutrons emitted at 0°, 90°, and 180° to the disintegrating γ-ray is measured with two boron chambers surrounded by paraffin. Corrections for geometrical conditions, scattering by the room and scattering by the heavy water have to be applied. For the latter correction only an approximation is found by extrapolating the results obtained with two spheres (16-mm and 8-mm diameter) to radius zero.

Under the assumption that the angular distribution can be described by a spherically symmetrical component and a $\sin^2$ component, the cross section σ_a for the spherically symmetrical component is found to be

$$\sigma_a = (0.39 \pm 0.12) \times \sigma_{\text{total}}.$$

Taking $\sigma_{\text{total}} = 10 \times 10^{-28}$ cm^2 (a value published in 1938, which is most likely too low), one obtains $\sigma_a = (3.9 \pm 0.12) \times 10^{-28}$ cm^2, as compared to $\sigma_m = 3.4 \times 10^{-28}$ cm^2, the cross section calculated for the magnetic photo-effect from the experimental cross sections for the scattering and capture of slow neutrons by protons.