Angular Distribution of Neutrons from the Photo-Disintegration of the Deuteron*

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The angular distribution of neutrons arising from the photo-disintegration of deuterons by gamma-rays of 2.76 Mev energy has been investigated under conditions requiring no corrections for neutron scattering by the walls or by the heavy water. Inverse square law tests using balloon suspension indicated the clearance required for which the apparatus was free of the effects of scattering. The weighted ratio of the photomagnetic to the photoelectric cross sections was found to be 0.295±0.036.

INTRODUCTION

WITHIN the past decade, a considerable amount of effort has been expended by numerous investigators[1-5] toward the experimental determination of the angular distribution with which neutrons or protons are ejected when deuterons are photo-disintegrated. These earlier attempts have in general been handicapped by low intensity; the rather weak effects attending photo-disintegration have made angular distribution measurements very difficult. In consequence, it has not been possible to attain the accuracy required for verification of the theoretical analysis from the experimental data.

The method to be reported here is an attempt toward a more satisfactory investigation of the angular distribution of the photo-neutrons using the 2.76 Mev gamma-rays from Na^{24}. An experimental arrangement was selected in which the geometrical conditions were such as to give improved definition of angle while at the same time providing a higher intensity photoneutron yield.

In the photo-disintegration of the deuteron, theoretical considerations[6] have indicated not only the existence of a photoelectric effect, i.e., the influence of the electric field of the gamma-ray upon the deuteron, but also of a photo-magnetic effect due to the magnetic field of the gamma-ray. In the former, the disintegrations are the result of electric dipole transitions of the deuteron; in the latter, a magnetic dipole transition is involved. It has been shown that the above two effects result in a superposition of a ^3P, i.e., $\sin^2$, distribution and a spherically symmetrical ^1S distribution, for the ejected nucleons in the center of gravity system. For photons whose energy is not too high, and therefore of small momentum, the center of gravity system may be identified here with the laboratory system.

Since the photo-disintegration differential cross section consists of two terms of different origin, it is possible to distinguish one from the other by the difference in their dependence on the angle of ejection of the nucleons with respect to the direction of the incident photon. Thus, experimental evaluation of the ratio of intensities of the ejected neutrons at two different directions with respect to that of the incident radiation is required. This will lead to an evaluation of the ratio of the total magnetic to the total electric cross sections, $\tau=\sigma_m/\sigma_{el}$.

During the concluding weeks of the current investigation, several brief articles[7-9] have appeared in the literature giving the results of recent experiments designed to measure the angular distribution of neutrons or protons produced by photo-disintegration of the deuteron. In general, only preliminary results are reported. Nevertheless, comparisons may be drawn between the numerical results of these investigations and that to be reported here.

EXPERIMENTAL APPARATUS

The gamma-ray sources were prepared by cyclotron bombardment of sodium with deuterons. Sodium metaborate targets were prepared by fusing 40 mg of the compound onto the grooved face of a copper target head of 1.7 cm diameter. By internal bombardment with beam currents of 350 microamperes at 7 Mev for six to eight hours, it was possible to prepare sources having strengths up to 500 millicuries.

The neutron detector consisted of a proportional counter containing BF_3 at one-third of an atmosphere of pressure. The gas was extracted from a boron trifluoride-calcium fluoride complex. As furnished by the Atomic Energy Commission, Isotopes Branch, the boron in the complex is 96 percent B^{10}. By the addition of 10 percent of argon of 99.6 percent purity, it was possible to hold the operating potential of the counter down to a value of 2100 volts. The over-all length of the cylindrical counter was 8 inches; its diameter was $1\frac{1}{2}$ inches. A three mil tungsten wire served as the anode.

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[1] Chadwick, Feather and Bretscher, Proc. Roy. Soc. **A163**, 366 (1937).
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[9] Meiners, Smith and Slack, Phys. Rev. **75**, 1632 (1949).

The pulses produced by the disintegration products from the capture of slow neutrons by B^{10} in the reaction $B^{10}(n,\alpha)Li^7$ were amplified by a general purpose linear amplifier constructed on the design developed by Jordan and Bell.[10] After the signals were differentiated and amplified, they were allowed to pass through a discriminator or pulse height selector so that only pulses larger than a selected value were recorded by a scaling circuit. With proper selector setting, it was readily possible to exclude all but those pulses arising from the above reaction. Extreme care was exercised in the construction and operation of the apparatus to exclude all background of mechanical and electrical origin. External sources of interference which could give rise to spurious counts were minimized by operating only at night.

The counter was surrounded by a paraffin form which acted as a moderator for slowing down the fast neutrons produced in the photo-disintegration process. A cadmium covering of 10 mil thickness completely surrounded the detector. Preliminary tests showed that an increase by a factor of approximately four or five in the number of counts recorded could be gained by orienting the cylindrical counter so as to present a side view instead of an end view to the incident photo-neutron beam. Experimentally, the optimum paraffin thickness necessary for maximum counting efficiency was found by irradiating 25 cc of D_2O with gamma-rays from radiosodium. By interposing 1-cm slabs of paraffin between the neutron source and counter, a maximum counting efficiency was found for a thickness of approximately 5.5 cm of paraffin. Guided by these results, a paraffin form was constructed such that the front portion facing the neutron source was cylindrical in shape with axis parallel to the counter axis and of 5.5 cm paraffin thickness while the rear portion was a hemisphere of 15.5 cm diameter. For purposes of symmetry, the front cylindrical portion was then machined so as to present a circular area of 15.5 cm diameter through which the photo-neutrons had to pass in order to be detected. Only those neutrons emitted by the heavy water and contained in an angular opening of 5° could be slowed down and detected in the paraffin. As shown in Fig. 1, the detector was maintained at a fixed distance of 177.6 cm from the heavy water in order to give the desired angular opening.

To gain a high intensity of photo-neutrons a large volume of heavy water is desirable. However, three factors militate against such a choice: the increase in photo-neutron internal scattering with increase in volume, the departure from a point source of neutrons, and the increase in the angular opening for the gamma-rays effective in producing photo-disintegration. To avoid these objections and still permit effective use of as much as 30 cc of D_2O at one time, a toroid or anchor ring of small diameter copper tubing (0.08-cm wall thickness) was filled with heavy water and placed concentric with the axis of the apparatus. The toroid had a radius of 10 cm; the internal diameter of the copper tubing, and hence, of the heavy water was slightly less than 8 mm. With this choice of geometry, it was possible to meet the requirements satisfactorily. Scattering by the heavy water was thereby reduced to a value not detectable outside the probable error of the data (see below); the point source requirement considering the distances involved was essentially satisfied; and the angular opening of the gamma-rays was maintained within a value of 8.4° or less.

The sodium source was located on the axis of the heavy water toroid. By positioning the source at specified distances from the plane of the toroid and concentric thereto, it was possible to vary the angle, γ, between the primary gamma-rays and the observed photo-neutrons. Figure 2 serves to illustrate the arrangement of the principal components of the apparatus. It is apparent that this geometry is such as to select for detection only those neutrons having the same direction (within the angular openings allowed the neutrons and the gamma-rays) with respect to the primary gamma-rays. As this direction is changed by

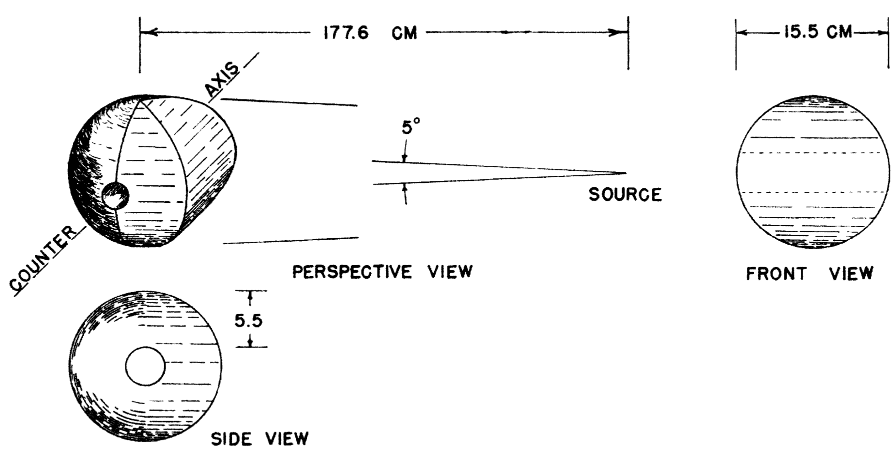

FIG. 1. Paraffin moderator.

[10] W. H. Jordan and P. R. Bell, Rev. Sci. Inst. 18, 703 (1947).

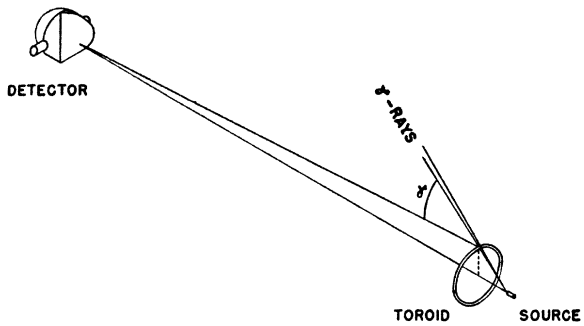

FIG. 2. Experimental set-up (not to scale).

movement of the sodium source, the gamma-ray flux traversing the toroid is likewise changed, thereby necessitating a solid angle correction for the intensity. To keep this correction factor within a reasonably small range of values, the angle, γ, was varied only from 90° to 45° in 15° steps. This required motion of the source throughout a total distance of 11 cm as measured out along the axis of the toroid. For angles less than 45°, this distance increases rapidly with consequent decrease in neutron production. Hence, measurements at the smaller angles were avoided. The gamma-rays effective in producing photo-disintegration had a variable opening due to the finite size of the source and to the fact that the source distance varied with the angle, γ. These angular openings corresponding to γ-angles of 90°, 75°, 60° and 45° were 5.1°, 7.2°, 8.4°, and 7.8°, respectively. Figure 3 shows a dimensional view of the apparatus to scale.

SCATTERING BY THE HEAVY WATER

The extent to which the photo-neutrons scattered by the heavy water affect the angular measurements may be determined by a separate investigation. So far as the isotropic component of the photo-effect is concerned, the scattering would have no influence upon the measured angular distribution. This is not the case, however, for the $\sin^2$ component. The net result of scattering would be to enhance the isotropic component at the expense of the anisotropic component. For this reason, the effect of the scattering by the heavy water must be kept small.

To investigate the optimum toroid dimensions which would allow substantial intensity without excessive scattering, the following test was conducted. Into each of four 10-cm radius toroids having inside sectional diameters of 0.439, 0.630, 0.795, and 1.092 cm a constant volume (9.53 cc) of D_2O was added. This volume completely filled the 0.439 cm toroid. The remaining toroids were then filled to full capacity with H_2O such that the ratio of H_2O to D_2O was 0, 0.98, 2.16 and 5.23, respectively.

Using toroids filled in this manner, it was possible to investigate the effect of the increased volume of water upon the scattering while at the same time to hold constant the number of photo-neutrons produced in the photo-disintegration process. Any change in the number of neutrons detected with change of toroid could quite correctly be attributed to the effect of the additional water upon the scattering. This method has the obvious disadvantage of using the scattering in H_2O to tell us something about the scattering in D_2O.

A radio-sodium source was prepared by a six and one-half hour cyclotron bombardment at an average deuteron beam current of 350 microamperes. Observations of one hour duration using the arrangement shown in Fig. 2 were made for each toroid. Two background observations, each of one hour duration, were made near the start and at the end of the run—an empty copper toroid replacing the water-filled toroids during these periods. This background amounted to an average value of 1.29 counts per minute with the sodium source still positioned on the apparatus. Because of the decay of the sodium source with half-life of 14.8 hours during the course of an experimental run, it was necessary to apply a decay correction factor to the data so as to normalize the counting rates to a constant source intensity. The data from this test for $\gamma=90°$ are shown plotted in Fig. 4.

The interpretation given to this result rests in general upon the fact that, within the probable error of the data, no increase in intensity is apparent for toroid volumes up to 30 cc for which the radius of the toroid section is 0.398 cm. As the volume becomes greater, however, those neutrons which travel in the plane of the toroid have greater probability for scattering since their

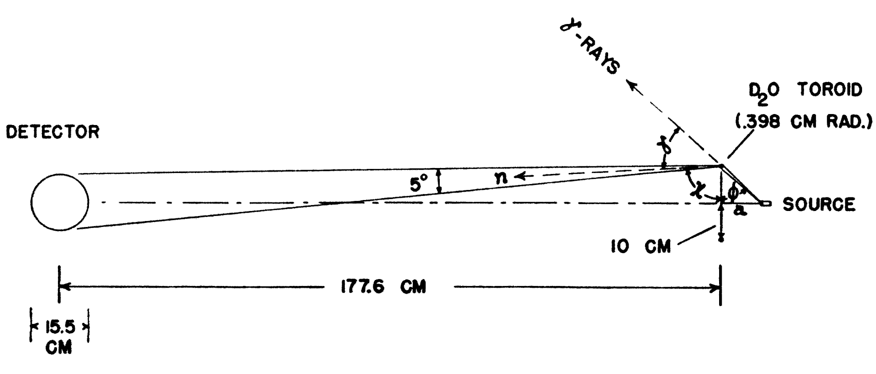

FIG. 3. Dimensional view of apparatus (scale: 1 cm = 10 cm).

path lengths in water have become greater. Hence, some neutrons which were not initially directed toward the detector may now suffer single or multiple scattering and be recorded. These scattered neutrons augment the unscattered intensity recorded for the smaller volumes. Thus, a rise in the curve sets in at volumes for which the amount of scattering is detectable outside the probable error of the counting rate. In consequence, the 0.398-cm radius toroid was used throughout all subsequent angular distribution tests. This choice permitted as large a neutron intensity as possible consistent with a minimum detectable scattering effect.

SCATTERING BY THE WALLS

A potential source of error in experiments in which fast neutrons are formed at one position and detected as slow neutrons at another position removed from the source is that due to scattering of neutrons by parts of the apparatus and by the walls of the room. The material forming the framework of the apparatus and the supports for holding the components of the apparatus at fixed positions were kept as small as possible to make their contribution to this effect negligible. However, the contribution from the walls of the room may be considerable. For this reason, it was necessary to measure the scattered neutron intensity to determine the extent to which this effect influenced the experiment.

The scattering by the walls of the room was studied by measuring the deviations from the $1/r^2$ law for the neutrons observed with the detector at various distances from a small photo-neutron source. For this purpose, a freshly bombarded Na^{24} source was surrounded by a metal cup containing 190 cc of heavy water. This, and the detector heretofore described, were mounted six feet above the floor of a medium sized laboratory room whose dimensions in meters was $7\times 14\times 4$. Readings of the neutron intensity were made with the photo-neutron source placed at various distances from the detector. The latter was maintained at a fixed position in the center of the room.

The results of this test, corrected for decay of the source and with background (approximately one count/min.) subtracted, are shown in the upper curve of Fig. 5. Here the photo-neutron intensity per minute and distance in meters are plotted on logarithmic scales. It is apparent that the deviation from the inverse square law is extremely large; the exponent evaluated for these data was found to be -1.15.

In consequence of this result, the apparatus was next mounted on the parapet fringing the roof of a four-story laboratory building. The detector, still supported on a thin stand six feet high, was placed at one corner of the parapet. Its over-all height above the roof was $8\frac{1}{2}$ feet. The neutron source, consisting of 150 cc of heavy water surrounding a Na^{24} target of approximately 400 mc strength, was similarly mounted on top of the parapet. By moving the source at various intervals along one side of the building, the variation of intensity at the detector could be recorded.

The data resulting from this test, when corrected for decay and with background (approximately 3 counts/min.) subtracted, are shown marked "roof-top" in Fig. 5. These data have been normalized at the one meter position with the previous data taken indoors. A considerable improvement toward an inverse square fall-off is apparent with the exponent now decreasing to -1.66.

To reduce still further the effect of neutron scattering by the surrounding objects, the equipment was adapted so as to permit measurements aloft. Ten Neoprene captive balloons, each inflated with hydrogen to a diameter of six feet, provided sufficient lifting force to raise the twenty-five pounds of equipment consisting of cadmium-covered paraffin moderator, counter and counter basket, preamplifier, filter box, heavy water cup and source, five-conductor shielded cable, and unshielded high voltage cable. The ten balloons were

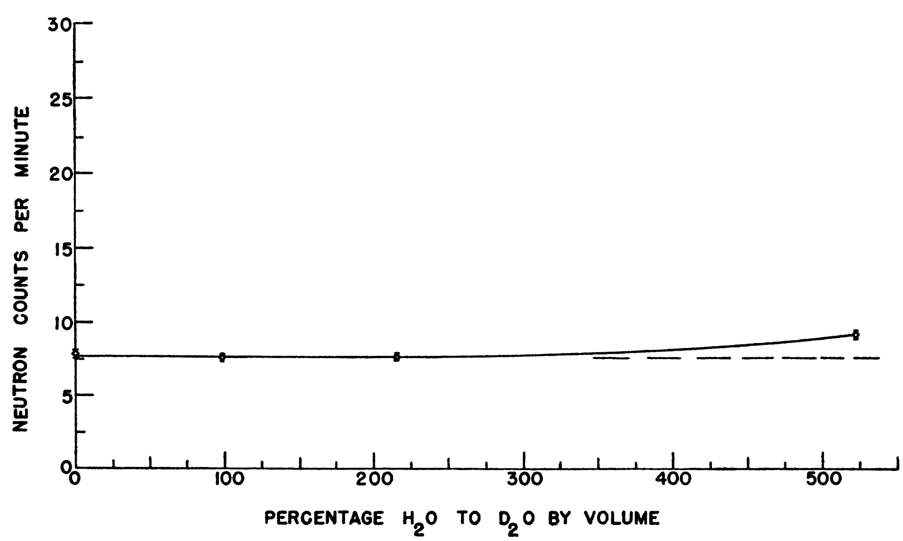

FIG. 4. D_2O scattering test.

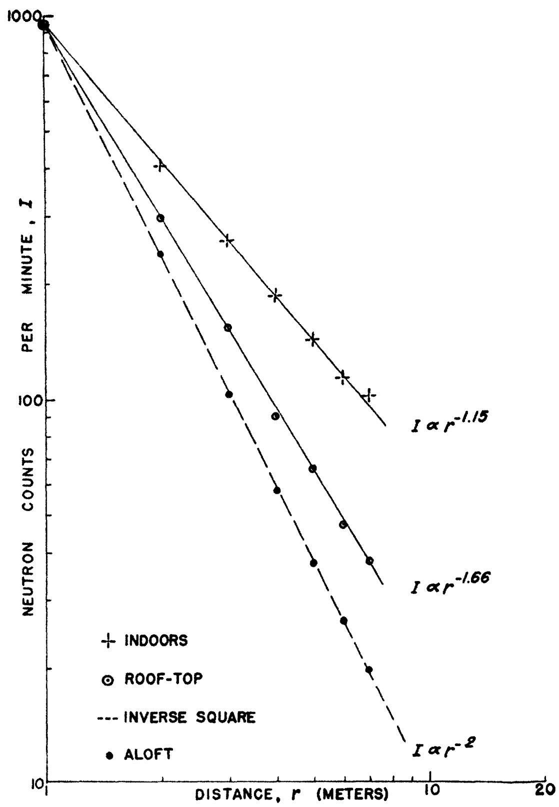

FIG. 5. Photo-neutron background.

linked together into a compact group so as to minimize excessive jarring of the apparatus which otherwise would occur if the ballons were allowed to separate and then be blown against each other. The balloons were positioned approximately one hundred and twenty-five feet above the apparatus so as to minimize the effect of scattering by the hydrogen gas. The distance between source and detector was made variable in intervals of one meter by linking together a number of one-meter sections of $\frac{1}{16}$-inch stranded steel cable with snap hooks. By lowering the apparatus, sections of cable would be quickly added or removed as desired. During the course of a run, the apparatus was maintained at an average distance of sixty feet from the building.

Figure 6 shows an approximately vertical view indicating the manner in which the apparatus was suspended from the mooring line. The weight of the power cables was removed from the detector by looping these back to the line as shown.

Using 190 cc of D_2O, intensity measurements were taken at six positions in random order. The data corrected for decay of the source and for background (approximately three counts/min.) are shown plotted in Fig. 5. The dashed line is that corresponding to an inverse square fall-off.

The consistency of the data in obeying the inverse square law when the apparatus is kept clear of walls is apparent. To make unambiguous tests on the angular distribution, these results show that it will be sufficient to suspend the apparatus outdoors and at least sixty feet away from surrounding objects. Such a procedure will effectively eliminate the need for a wall scattering correction to the data.

MEASUREMENTS USING OUT-OF-DOOR SUSPENSION

The conduct of the experiments on the angular distribution measurements was next altered to permit an out-of-doors test without the use of ballons. For this purpose, a three-hundred foot suspension cable ($\frac{1}{8}$-inch stranded steel) was fastened so as to extend between structures atop the roofs of two four-story buildings. The apparatus previously described and shown suspended in Fig. 7 was equipped with Nylon lines to permit its being drawn out with the aid of pulleys to a point midway between and slightly above the two buildings. In this fashion the equipment remained suspended one hundred feet from the buildings and approximately ninety feet above the ground. Checks on the inverse square law in the manner described above showed that with this arrangement the wall scattering effect was absent when the apparatus occupied the operating position at the center of the cable.

In the conduct of the angular distribution measurements, the activated source of sodium, mounted on its support rod, was placed in the aluminum holder located

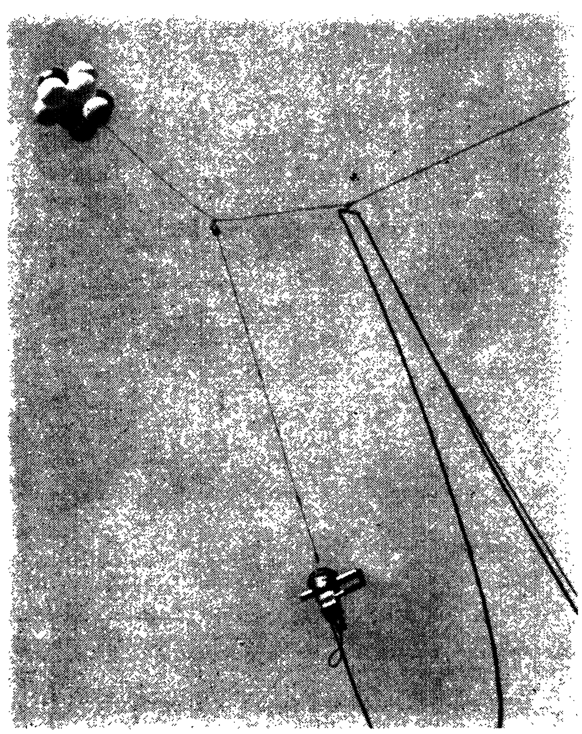

FIG. 6. Apparatus for inverse square law test in flight—vertical close-up.

above the toroid in the upper frame of Fig. 7. An empty or heavy water filled toroid shown clamped to the wire basket allowed either a background or an angular distribution measurement. The detector, with accompanying preamplifier and filter box, was supported by the four $\frac{1}{16}$-inch stranded cables which extended down from the toroid as shown in the lower frame of Fig. 7. These cables in turn fastened to an empty copper toroid which encircled the top portion of the cadmium-covered paraffin form. This toroid served to prevent the cables from cutting into the paraffin. Only the sensitive volume of the counter was enclosed in the paraffin. The horizontal portions seen extending beyond the form on either side consisted of the shielding caps and sleeves and were not regions sensitive to neutron detection. However, these portions were covered with sheet cadmium to permit absorption of slow neutrons which approached the sensitive volume from either end of the counter.

Between measurements, the apparatus was drawn in, the source reoriented to a new position by means of stop grooves in the source support rod, and then drawn out to its operating position at the center of the suspension cable.

A total of six complete and independent measurements were made of the intensity at each of the 45°, 60°, 75°, and 90° positions. Each measurement at a single position lasted for one hour.

The total number of neutron counts (less background) recorded at each position during the six one-hour observation periods is shown in Table I, column 2. The average background in these tests was 1.77 counts per minute.

The neutron intensity recorded at each angular position requires the application of several correction factors before useful information may be obtained from the data. One such correction relates to the decay of the radio-sodium source during the period of observation; a second correction must be applied to the recorded intensity by virtue of the fact that the gamma-ray flux streaming through the heavy water toroid varies with the axial distance "a". The values of this correction factor ranged from 1.00 at the 90° position to 2.23 at the 45° position. Application of these corrections yields the average number of counts per minute, $\bar{I}$, shown in column 3 of Table I. The probable error associated with each counting rate is likewise presented in this same column.

RESULTS AND CONCLUSIONS

From the results of theoretical analysis of the nuclear photo-effect, we consider that the total cross section consists of an isotropic component due to magnetic interaction and an anisotropic component due to electric interaction. The differential cross section of the latter is expected to conform to a $\sin^2$ distribution. In consequence, we assume that, at the angle, γ, the average intensity of the photo-neutrons can be described by a relation of the form

$$\bar{I}(\gamma)=\frac{\int_{\gamma_1}^{\gamma_2}(a+b\sin^2\gamma)\sin\gamma d\gamma}{\int_{\gamma_1}^{\gamma_2}\sin\gamma d\gamma}, \qquad (1)$$

where the limits of integration are chosen to include the total angular opening allowed the photo-neutrons and primary gamma-rays by the finite size of the detector and toroid. The constants, a and b, represent the number of photo-neutrons projected into unit solid angle, at the angle $\gamma=90°$, by the magnetic and electric photo-effects, respectively.

Upon integration, we obtain for the average intensity at the angle, γ, and for the angular opening from γ_1 to γ_2, the value

$$\bar{I}(\gamma)=a+b-\tfrac{1}{3}b(\cos^2\gamma_1+\cos\gamma_1\cos\gamma_2+\cos^2\gamma_2). \qquad (2)$$

The ratio of the intensities corresponding to measurements taken at two different γ-angles will yield information on the value of the quotient, a/b. Designating the ratio of intensities measured at the γ-angles, γ_A and

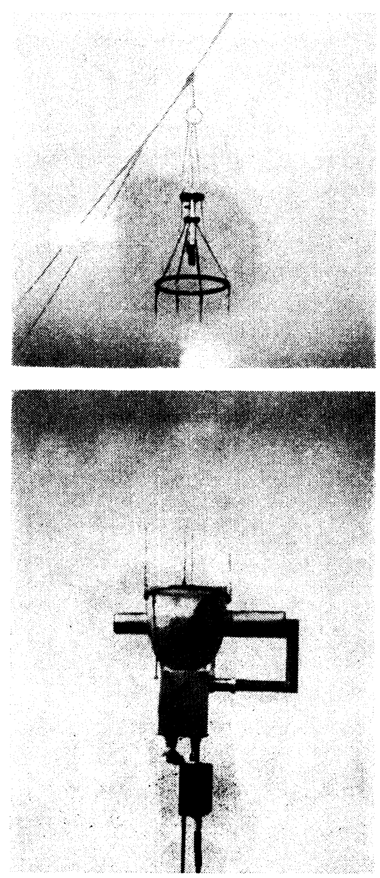

FIG. 7. Apparatus for angular distribution test in suspension—composite close-up.

TABLE I. Composite angular distribution data.

1 γ-angle	2 Total no. counts	3 $\bar{I}$, average no. of counts/min. (corrected)
45°	1415	9.34±0.23
60°	2929	12.66±0.19
75°	4307	15.03±0.18
90°	5133	15.94±0.17

γ_B, by the symbol $B_{A,B}$, we have, therefore, a set of equations as:

$$(a/b)_{A,B}=\frac{B_{A,B}\{1-\frac{1}{3}(\cos^2\gamma_3+\cos\gamma_3\cos\gamma_4+\cos^2\gamma_4)\}-\{1-\frac{1}{3}(\cos^2\gamma_1+\cos\gamma_1\cos\gamma_2+\cos^2\gamma_2)\}}{1-B_{A,B}}, \quad (3)$$

where γ_1 and γ_2 represent the integration limits associated with the angle γ_A, while γ_3 and γ_4 represent the corresponding limits for the angle γ_B.

Upon applying the average counting rates per minute, $\bar{I}$, of Table I to the above set of equations, we obtain values for the quotient, a/b, corresponding to all possible combinations of pairs of angles at which observations have been made. A probable error to be assigned each of these quotients was evaluated in accordance with standard practice by propagating the errors listed in Table I through the various mathematical operations indicated in Eqs. (3).

Because the probable error of the counting rate (column 3, Table I) is larger the smaller the γ-angle, the resulting percentage errors of the quotients, each of which involves intensity measurements at two γ-angles, will vary over wide limits. For this reason, it is desirable to evaluate a weighted average, $\langle a/b\rangle_{Av}$, in such fashion that greater emphasis is placed on those quotients having the smaller error. To this end, a weighting factor was assigned to each quotient which is inversely proportional to the square of the probable error of that quotient.[11] This procedure permits evaluation of a grand mean and its probable error in accordance with Eqs. (27) and (28), Chapter VIII, of the reference cited. The value so obtained is:

$$\langle a/b\rangle_{Av}=0.196\pm0.024.$$

From this experimental result, we obtain the ratio, τ, of probabilities of the magnetic to the electric effect, since $a/b=\frac{2}{3}\tau$. Hence, for the Na^{24} gamma-ray energy of 2.76 Mev we have

$$\tau=0.295\pm0.036.$$

The ratio of the photo-magnetic to the total cross section becomes, therefore

$$\tau/(\tau+1)=0.228\pm0.028.$$

The value of a/b from this investigation is found to lie below that of Lassen[7] who gives a value of 0.22±0.04. On the other hand, it exceeds the Hamermesh and Wattenberg value of 0.15±0.04 which was revised downward from 0.24 after publication of the Bulletin.[8]

In consequence of the difficulties attending the measurement of the weak effects associated with photodisintegration by current techniques, verification of the existence of the additional $^3D-^3P$ and $^3D-^1D$ transitions predicted by non-central force theory, lies well beyond present experimental capabilities.

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Finally, the stimulation and encouragement afforded me through the Horace H. Rackham Special Fellowship appointments for the school years 1947–1948 and 1948–1949 are gratefully acknowledged.

[11] A. G. Worthing and J. Geffner, *Treatment of Experimental Data* (John Wiley and Sons, Inc., New York, 1943).

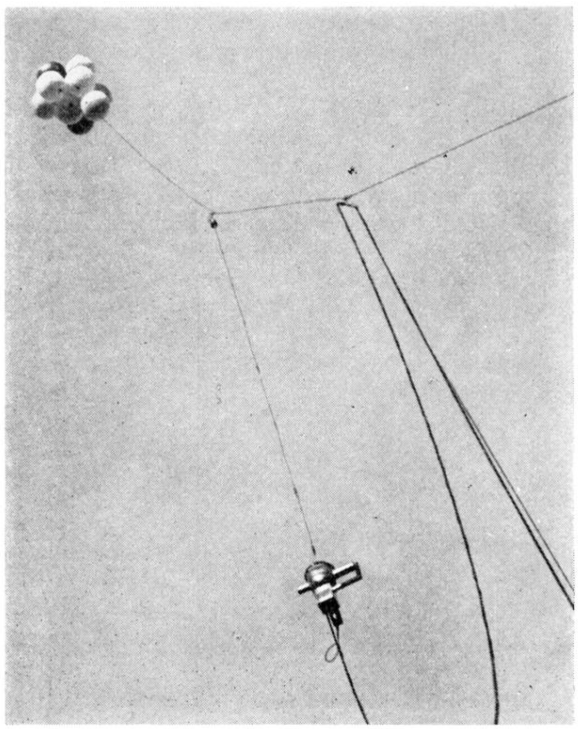

FIG. 6. Apparatus for inverse square law test in flight—vertical close-up.

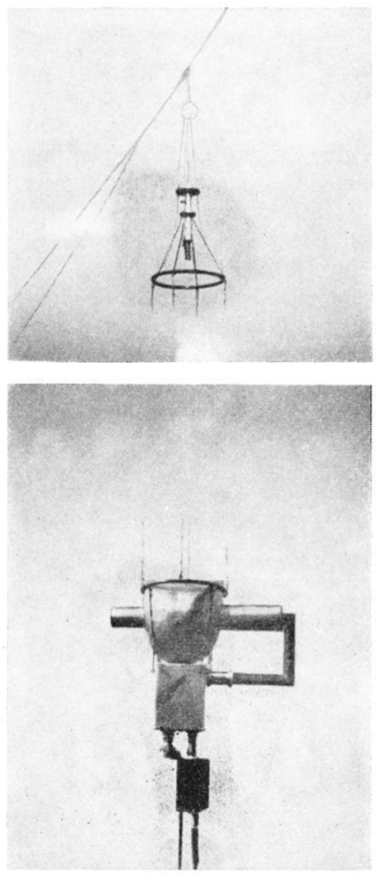

FIG. 7. Apparatus for angular distribution test in suspension—composite close-up.