# Photo-Disintegration of the Deuteron*

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A study of the photo-disintegration of the deuteron using a cloud chamber as a detector has been made for gamma-ray energies of 6.14 and 7.00 Mev from the $F(p, \alpha)O^{16*}$ reaction. By observing the number of photo-disintegration protons and the number of electron pairs formed in the gas ($CD_4$) of the cloud chamber, the ratio of the photo-disintegration cross section to the pair cross section is obtained. Assuming a calculated value for the pair cross section these data yield $\sigma[D(\gamma, p)n]=25.7$ (14 percent P.E.)$\times 10^{-28}$ cm² at an average gamma-ray energy of 6.55 Mev.

A plot of the angular distribution of the photo-disintegration protons agrees, within statistical limits, with $\sin^2\theta$, though there may be a slight asymmetry in the forward direction.

## I. INTRODUCTION

THIS is a report of an experiment designed to measure the angular distribution of the photo-protons and the cross section of the photo-disintegration of the deuteron at a gamma-ray energy of about 6.5 Mev. As far as is known there have been reported two other experimental results for the cross section in this energy range. Van Allen and Smith[1] obtained a value of $11.6\pm1.5\times10^{-28}$ cm² with a gamma-ray energy of about 6.2 Mev and Barnes, Stafford, and Wilkinson[2] give $21.5\pm1.2\times10^{-28}$ cm² at about 6.2 Mev.

In the present experiment it was thought that the cross section might be obtained by observing the photo-disintegration of the deuteron together with a second process, pair production, whose cross section is rather well known. The cross section for the production of electron pairs has been experimentally determined by several observers[3] and found to agree with the theory for light elements. Thus, one might obtain the cross section for the photo-disintegration ($\sigma_{pd}$) by counting the number of disintegration protons ($N_p$) and electron pairs ($N_{\text{pairs}}$) occurring in a medium containing deuterium under the same conditions by

$$\sigma_{pd}=(Z^2)_{ef}\sigma_{\text{pairs}}N_p/N_dN_{\text{pairs}}, \tag{1}$$

where $N_d$ is the number of deuterons per molecule, $(Z^2)_{ef}$, the effective $Z^2$ per molecule of the medium, and $\sigma_{\text{pairs}}$ the cross section for the production of electron pairs.

A Wilson cloud chamber was used as the detector. Since the equipment and techniques were essentially the same as previously reported,[4] they will not be described here.

## II. SENSITIVITY OF THE CLOUD CHAMBER

There may be some objection to the use of a cloud chamber as here employed, in that there is some question whether the sensitivity of a cloud chamber is the same for proton and electron tracks. It is well known that electron tracks may be discriminated against when it is desired to observe only heavy particle tracks by decreasing the expansion ratio. Thus, when a cloud chamber is adjusted for good electron tracks, is the cloud chamber equally sensitive for heavy particles and electrons?

To obtain information on the behavior of the cloud chamber a small quantity of uranium nitrate was placed on a thin foil of collodion which was then placed in the chamber. Assuming that the uranium was in secular equilibrium with its immediate daughter products there should, on the average, be one alpha-particle for every beta emitted by the uranium.

Figure 1 shows the data obtained from uranium; Fig. 1(a) the ratio of the number of alphas to betas as a function of the time after expansion. Within statistical error it is constant from 0.2 sec. to 0.6 sec. after ex-

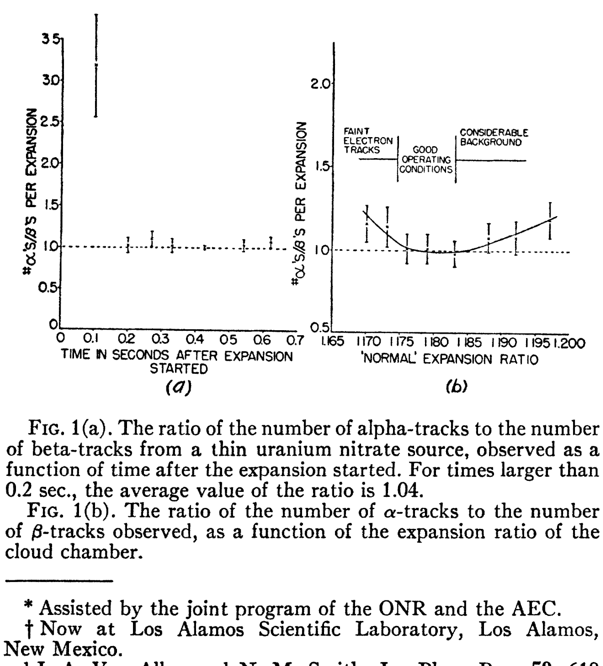


FIG. 1(a). The ratio of the number of alpha-tracks to the number of beta-tracks from a thin uranium nitrate source, observed as a function of time after the expansion started. For times larger than 0.2 sec., the average value of the ratio is 1.04.

FIG. 1(b). The ratio of the number of α-tracks to the number of β-tracks observed, as a function of the expansion ratio of the cloud chamber.

* Assisted by the joint program of the ONR and the AEC.
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[1] J. A. Van Allen and N. M. Smith, Jr., Phys. Rev. **59**, 618 (1941).
[2] Barnes, Stafford and Wilkinson, Nature **165**, 69 (1950).
[3] G. D. Adams, Phys. Rev. **74**, 1707 (1948); J. L. Lawson, Phys. Rev. **75**, 433 (1949); R. L. Walker, Phys. Rev. **76**, 527 (1949).
[4] J. A. Phillips and P. G. Kruger, Phys. Rev. **76**, 1471 (1949).

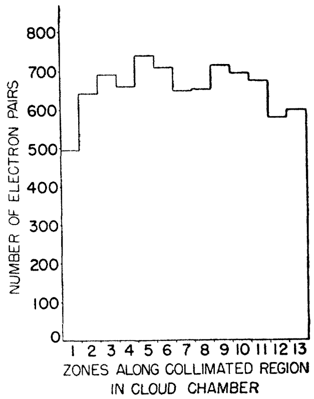



FIG. 2. Number of pairs observed per cylindrical volume element along the gamma-ray beam, in the usable portion of the chamber. These elements were 1.35 cm long and 2.54 cm in diameter. The usable porportion of the chamber was 17.6 cm long, and was illuminated by a light beam 3.3 cm high. Thus, all tracks starting in this volume could be seen easily.

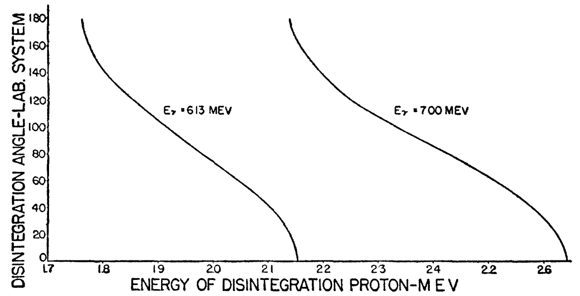



FIG. 3. Calculated values of the energy of the disintegration proton at various disintegration angles, $\theta$, in the laboratory system, for gamma-ray energies of 6.13 Mev and 7.00 Mev. In this experiment, $\theta$ is defined as the angle made by the disintegration proton and the initial direction of the gamma-ray.

pansion, and accordingly the pictures were taken 0.45 sec. after expansion during the experiment.

The average value of the ratio during this time interval is $1.04 \pm 3$ percent. Actually, since beta-rays with energy less than 10 kev would probably not be seen in these pictures the observed ratio should be larger than unity. To obtain an idea of what ratio we should reasonably expect, an estimate of the ratio of the number of $\beta$'s of energy less than 10 kev to the total number of $\beta$'s from $UX_1$ and $UX_2$ has been made using Marshall's[5] data. This gives a ratio of 1.06 with an error which is difficult to assess. Since the observed ratio is 1.04 it is assumed that some but not all beta-rays of energy less than 10 kev are observed and that, essentially, the test agrees with the expected ratio.

The ratio of alphas to betas as a function of the expansion ratio is shown in Fig. 1b. The pictures were taken 0.45 second after the expansion of the cloud chamber. It is seen that if the chamber is adjusted for good electron tracks there is some latitude permissible in the expansion ratio without changing the ratio of alphas to betas.

A further check was made for the sensitivity of the cloud chamber for electron tracks. Figure 2 shows the distribution of the electron pairs obtained during the experiment as a function of the distance of the track origin along the axis of the collimated gamma-ray beam. Apparently the chamber was uniformly sensitive to electron tracks throughout the collimated region. Thus, it may be said from the data in Figs. 1 and 2, that whatever be the sensitivities of the chamber for protons and electrons they are constant within statistics under the conditions of the experiment.

### III. SOURCE OF GAMMA-RAYS

The reaction $F^{19}(p, \alpha, \gamma)O^{16}$ was used as the source of gamma-rays with 5 Mev protons from the cyclotron of the University of Illinois. In the present experiment the energies of the gamma-rays were determined by measuring the range of the disintegration proton and its angle with respect to the incident gamma-rays.

The energy, $E_p$, of the disintegration proton as a function of angle $\theta$ for the two gamma-ray energies of 6.13 Mev and 7.00 Mev has been calculated by the equation

$$2E_p = h\nu(1 - h\nu/2Mc^2) + h\nu(P/Mc)\cos\theta - E, \quad (2)$$

where $h\nu$ is the energy of the gamma-ray, $M$ is the mass of the proton, $P$ is the momentum of the proton, and $E$ is the binding energy of the deuteron, assumed to be 2.235 Mev. Figure 3 shows the results of these calculations. It is seen that there will be only a small energy region for which there will be doubt as to whether it is due to a 6.13-Mev gamma-ray and disintegrated in the forward direction or to a 7.00-Mev gamma-ray and disintegrated backwards.

The above equation can be solved for $h\nu$ and expanded by taking only the first two terms. There results

$$h\nu = \frac{2E_p + E}{(1 + B\cos\theta)} \left\{ 1 + \frac{2E_p + E}{2Mc^2(1 + B\cos\theta)^2} \right\}, \quad (3)$$

where $B = v/c$ for the proton. This equation was used to calculate the energies of the gamma-rays from the energies of the disintegration protons.

### IV. PROCEDURE

The procedure was essentially the same as that used previously.[4] The cyclotron was run continuously with a flop-gate preventing the beam from striking the target between expansions of the chamber. Immediately after the chamber had fully expanded the flop-gate was pulled aside. The average beam current was 9 $\mu$a of molecular hydrogen.

The cloud chamber was filled with $CD_4$ and its stopping power calculated using the Livingston and Bethe curves.[6] The composition of the gas with which the chamber was filled was determined by a mass spectrographic analysis. The pressure of the gas in the chamber (about 20 lb. gauge) as measured by a Bourdon type

[5] Marshall, Proc. Roy. Soc. London, **A173**, 397 (1939).

[6] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 268 (1937).

gauge was recorded several times a day together with the barometric pressure. The temperature of the chamber was automatically controlled to $\pm 0.2°C$ by cooling coils. The magnetic field in which the chamber was located has been described in reference 4.

In the earlier work[4] the collimation and shielding of the cloud chamber was found to be sufficient for gamma-rays but not for neutrons. Accordingly, for this experiment the chamber and mirror box were surrounded by 6 in. of paraffin. Also 16 in. of paraffin was placed in front of the gamma-ray collimator, inside of the tanks surrounding the cyclotron to remove neutrons from the background radiation. Subsequent events show that this shielding may not have been completely adequate; this will be discussed later.

A total of 33,658 pictures were taken with the cloud chamber. These were examined on a Diebold microfilm reader by two observers. All electron pairs, electron triplets, and heavy particle tracks regardless of range were recorded. Those pictures containing possible proton tracks were later replaced in the original camera and optical system and measured.

## V. ELECTRON PAIRS

The criteria for the selection of a countable electron pair were the same as previously used[4] with the added condition that the apex of an electron pair must lie in a volume covered by the collimated gamma-ray beam such that all of the range of a disintegration proton originating in this volume could be observed.

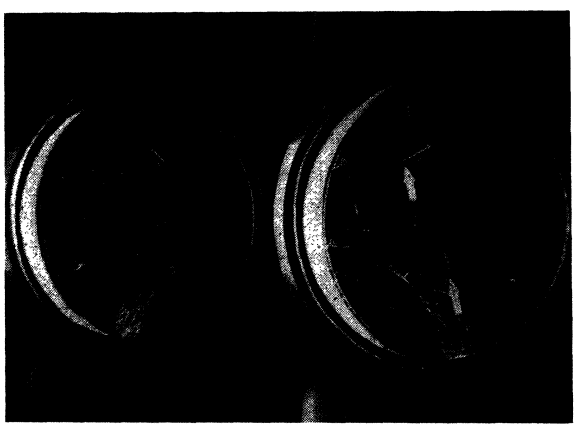


FIG. 4. Stereoscopic cloud chamber pictures showing a photoproton (upper arrow) and a pair (lower arrow) formed in the usable volume of the chamber.

The distribution of the electron pairs in the usable volume of the cloud chamber is shown in Fig. 2. It is seen to be a constant within statistical limits except for the first and last two divisions. The first division is low as this division lies in the path of Compton electrons leaving the side wall of the chamber through which the gamma-rays pass as they enter the chamber making the apex difficult to be clearly observed. Protons, however, will easily be seen in this region due to their greater ionization. The last two divisions are low for here it is difficult to be sure that the positive electron of a pair has the right curvature since the length of the track observable is short. Thus, several pairs would not be counted. The average over the middle ten intervals was used to correct for these three intervals. There results $9007 \pm 83$ electron pairs that occurred.

There is one further correction that must be applied to the number of electron pairs. The end of the recorded interval of an expansion was determined by the closing of the shutter of the camera. Since a proton track is much denser than an electron track the "exposure time" for the film to record a proton track is shorter than that for an electron track. Thus the effective detection time for a proton track is longer than for an electron track. By varying the aperture of the lens and the shutter speed it was determined that the camera was sensitive to electron tracks $7.8 \pm 5.2$ percent shorter than to proton tracks. With this correction $9710 \pm 476$ ($\pm 4.8$ percent) electron pairs occurred.

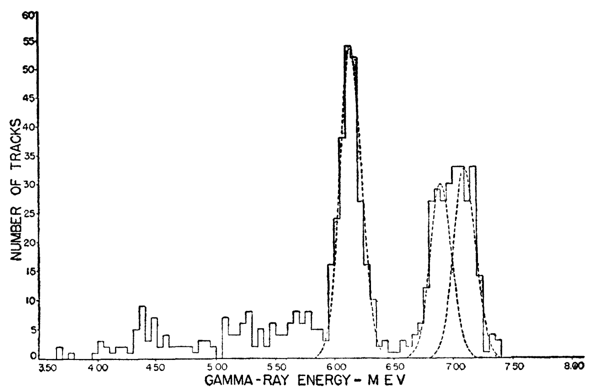



FIG. 5. Histogram of tracks starting in the collimated region showing the number of disintegration protons *vs.* the energy of the $\gamma$-ray causing the disintegration. This assumes that all measurable tracks whose full length was observable, were from the $D(\gamma, n)p$ reaction.

## VI. DISINTEGRATION PROTONS

All the proton tracks were viewed stereoscopically in the original optical system. The range, scattering angle, and azimuthal angle of each track were measured twice by a specially designed measuring engine.

Many of the proton tracks were observed to be badly "plumed," usually in the vertical direction. This is thought to be due to the chamber being overexpanded for proton tracks in order to obtain electron tracks. However, in most of these cases the original track could be observed through this plume and a reliable measurement made. An example of a sharp track is shown in Fig. 4.

The energies of the proton tracks whose entire range could be seen were calculated from their range and the stopping power, pressure and temperature of the gas. The energy of the incident gamma-ray was then calcu-

TABLE I. Calculation of angular distribution from tracks whose range can be measured.

| 7.00 Mev $\theta$ | $N$ Experimental tracks in first div. | $A$ Correction factor for geometry | $6NA$ (six div.) |
|---|---|---|---|
| 10 | 0 | 1.00 | 3 (total) |
| 30 | 4 | 1.02 | 24.4 |
| 50 | 25 | 1.04 | 156.0 |
| 70 | 35 | 1.06 | 222.2 |
| 90 | 44 | 1.09 | 287.2 |
| 110 | 24 | 1.05 | 151.0 |
| 130 | 19 | 1.02 | 116.0 |
| 150 | 6 | 1.00 | 36.0 |
| 170 | 0 | 1.00 | 2 (total) |
| 6.14 Mev | | | 997.8 |
| 10 | 0 | 1.00 | 0 |
| 30 | 5 | 1.01 | 30.3 |
| 50 | 9 | 1.02 | 55.0 |
| 70 | 27 | 1.03 | 166.9 |
| 90 | 24 | 1.03 | 148.2 |
| 110 | 16 | 1.02 | 97.9 |
| 130 | 19 | 1.01 | 115.2 |
| 150 | 8 | 1.00 | 48.0 |
| 170 | 3 | 1.00 | 0 |
| | | | 664.5 |

lated by Eq. (3). A histogram of the resulting gamma-ray energies are shown in Fig. 5. It is seen that there are two main groups, one at 6.14±0.05 Mev and the other at 7.00±0.06 Mev which are in good agreement with the authors[4] previous values from electron pair measurements and with reported values of others.[7]

The 7.00-Mev line appears to be much broader than the 6.14-Mev line. If one assumes a Gaussian distribution for the 6.14-Mev line and applies the same half-width to two lines at 6.90 and 7.10-Mev on can explain the total width of the 7.00-Mev line. The presence of two components in the 7.00-Mev line is also suggested by the report of three[8] groups of short range alphas to gamma-levels from this reaction. The gamma-ray energies of 6.9 and 7.1 would be in reasonable agreement with this picture. However, much better resolution would be necessary to show by this method that the 7.00-Mev group is double.

Since the light beam in the cloud chamber was not sufficiently high to permit the entire range of all tracks to be seen, there must be a correction to the number of tracks measured. The most straightforward method is to use only those tracks occurring in the first azimuthal distribution, 0 to 15°, interval. Correcting the number of tracks in the $\Delta\theta$ intervals of Table I by the calculated fraction of the total number in this interval which can be seen (correction factor for geometry in Table I) and multiplying by 6, the total number that would have been observed in all azimuths may be obtained. These calculations are given in Table I. There result 665±9.5 percent tracks in the 6-Mev line: 998±8 percent in the 7-Mev line and a total of 1663±6.1 percent tracks.

A second method of correction is as follows. From the range of the tracks (which varies with angle and with the energy of the gamma-ray) and the height of the light beam one can calculate the expected azimuthal distribution of these tracks where the entire range can be seen. Figure 6 shows this normalized, calculated, azimuthal distribution and the experimental distribution for the 6-Mev line. Assuming agreement within statistical error (since the data are divided into 9 groups for each line, the statistics in some intervals are very poor) the experimental numbers of protons observed can be corrected using the calculated fraction of the total number of tracks which would be observed. This calculation results in 642±6.5 percent tracks in the 6-Mev line: 1104±6 percent tracks in the 7-Mev line and a total of 1746±4.5 percent tracks.

While the results of both methods of correction agree within the standard deviation errors given, more confidence is placed in the first method because it involves only tracks whose full lengths could be seen and agree

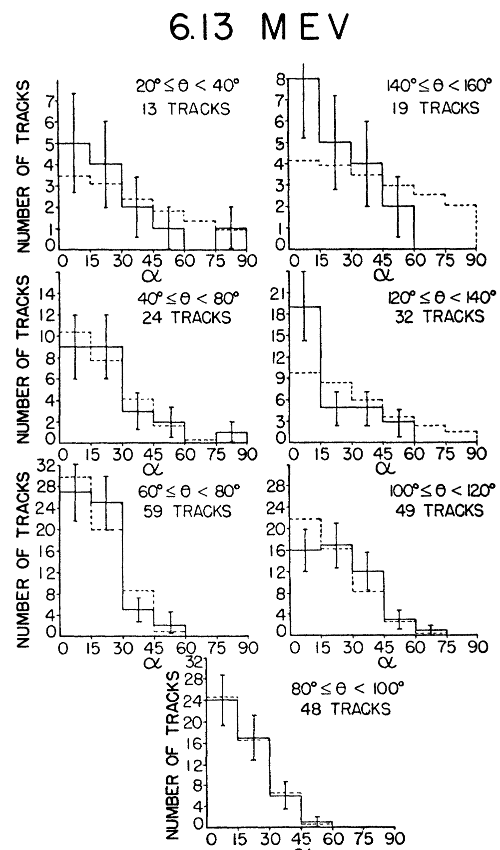



FIG. 6. Azimuthal distribution (folded 4 times) of observed tracks from the 6.13-Mev gamma-ray line, whose entire range was visible for various disintegration angles ($\theta$). The solid curves give the experimentally observed numbers, while the dotted curves are the theoretical distribution calculated from the geometry of the light and gamma-ray beams and the range of a photoproton falling in the $\theta$-interval under consideration.

[7] Rasmussen, Hornyak, Lauritsen, and Lauritsen, Phys. Rev. **77**, 617 (1950). R. L. Walker and B. D. McDaniel, Phys. Rev. **74**, 315 (1948).

[8] W. E. Burcham and J. M. Freeman, Phys. Rev. **75**, 1756 (1949). Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **78**, 88 (1950).

TABLE II. Photo-disintegration cross section.

| Gamma-ray energy Mev | Reference 12 $\sigma$(calc) $\times 10^{28}$ cm$^2$ | Authors $\sigma$(expt) $\times 10^{28}$ cm$^2$ | Barnes[a] $\sigma$(expt) $\times 10^{28}$ cm$^2$ |
|---|---|---|---|
| 6.14 | 22.4<br>20.1[c] | 26.9±3.8 | 21.5±1.2[b] |
| 6.55 | 21.4 | 25.7±3.7 | — |
| 7.04 | 20.2 | 24.2±3.4 | — |

[a] Barnes, Stafford, and Wilkinson, Nature **165**, 69 (1950).
[b] A summary of other experimental results may be found in I. F. E. Hanson and L. Hulthin, Phys. Rev. **76**, 1165 (1949).
[c] H. A. Bethe and C. Longmire, Phys. Rev. **77**, 647 (1950).

with the data of Fig. 3. Thus, these numbers will be used below in calculating the photo-disintegration cross section.

## VII. BACKGROUND CORRECTION

The background correction for heavy particle tracks is taken from the data of Fig. 5. Here it is seen that there are a number of heavy particle tracks that did not result from a photo-disintegration of a deuteron by either a 6-Mev or a 7-Mev gamma-ray. 583 electron pairs were measured and only 2.5 percent were found to have an energy low enough to explain these tracks. Thus, it is concluded that the heavy particle track outside of the 6- and 7-Mev lines must have been caused by deuteron recoils from neutrons that passed through the shielding around the cloud chamber, protons from the $D(n, 2n)p$ reaction or are protons from some similar process involving elements other than deuterium in the gas of the cloud chamber.

By taking the average background in Fig. 5 below 6 Mev and assuming that it remains constant up to 6.4 Mev, one must subtract 44/256 of 665 tracks (i.e., 114 tracks) in the 6-Mev line, giving a net number of 551±68 tracks (or ±12.3 percent) in the 6-Mev line. Between the two lines in the region of 6.5 Mev, there appear 14 tracks over a 0.3-Mev interval. Assuming this constant over the 7-Mev line, one must subtract 37/281 of 998 tracks which gives a net 867±90 tracks (10.3 percent) for the 7-Mev line. The total number of corrected proton tracks is now 1418±8 percent.

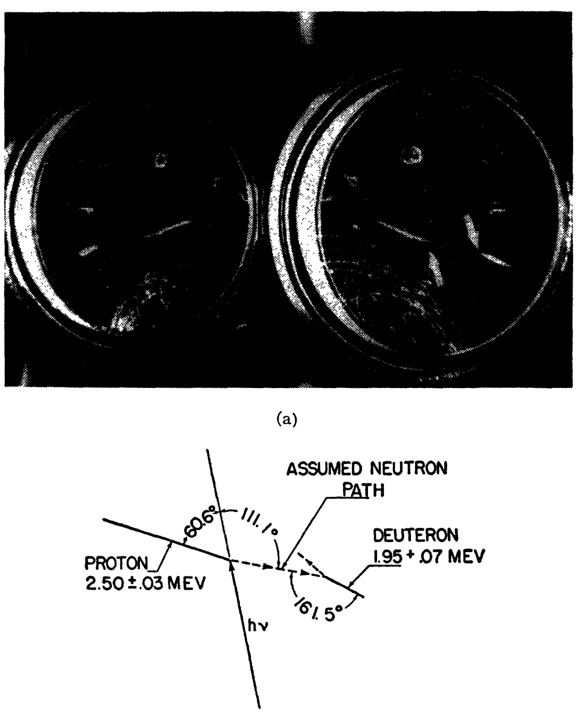



FIG. 7. Cloud-chamber picture (a) and schematic diagram (b) showing an $n-d$ scattering by a photo-neutron whose accompanying photo-proton is observable. The proton range and angle show the disintegration to have been caused by a 7.00-Mev gamma-ray. On this basis a deuteron scattered at 18.5° in the laboratory system by the photo-neutron should have 1.85 Mev, which agrees reasonably with the measured value of 1.95±0.07 Mev.

## VIII. EFFECTIVE $Z^2$ FOR THE GAS

To obtain a cross section for the photo-disintegration of the deuteron by this method it is necessary to know the cross section for electron pair production.

This has been calculated from a formula given by Hough[9] and corrected by 1.4 percent for screening according to Walker[10] to give: $\sigma_{\text{pairs}}(6.13\text{ Mev})=0.0611$ barn; $\sigma_{\text{pairs}}(6.55\text{ Mev})=0.0653$ barn; $\sigma_{\text{pairs}}(7.04\text{ Mev})=0.0699$ barn.

The composition of the heavy methane gas was determined by a mass spectrographic analysis to be,

| Component | Percent |
|---|---|
| $CD_3H$ | 9.2 |
| $CD_4$ | 85.4 |
| $N_2$ | 4.6 |
| $O_2$ | 0.8 |

A 50:50 mixture by volume of heavy alcohol and heavy water was used. The vapor pressures of the vapors are 24.3 mm of Hg for $C_2D_6O$ and 16.5 mm of Hg for $D_2O$ as given by Das Gupta and Ghosh[11] at 22.1°C. From the above, the effective $Z^2$ per molecule[4] is calculated to be 44.98 and the number of deuterons per molecule is 3.71.

From the above data the value of the cross section for the photo-disintegration of the deuteron is calculated to be $25.7\pm3.7\times10^{-28}$ cm$^2$ at an average gamma-ray energy of 6.55 Mev. The values given in Table II for 6.14 and 7.04 Mev are calculated from the value at 6.55 Mev by taking the ratios of the theoretical values obtained from Levinger's[12] formula. The two latter values are in agreement with the values obtained from the number of disintegration protons in each line and the calculated number of electron pairs in each line assuming a ratio of gamma-ray intensities[4] of 1.7 for the two lines.

[9] P. V. C. Hough, Phys. Rev. **73**, 266 (1948).
[10] R. L. Walker, Phys. Rev. **76**, 527 (1949).
[11] N. R. Das Gupta and S. K. Ghosh, Rev. Mod. Phys. **18**, 225 (1946).
[12] J. S. Levinger, Phys. Rev. **76**, 699 (1949).

TABLE III. Angular distribution for all tracks whose lengths can be measured.

| $\theta_{cm}$ | Number of tracks 6.15 Mev | Number of tracks 7.00 Mev | Total number both lines | Solid angle correction | Tracks per unit solid angle |
|---|---|---|---|---|---|
| 10 | 0.0± 0.0 | 3.2± 1.3 | 3.2± 1.3 | 0.0603 | 53.1±21.6 |
| 30 | 25.6± 7.4 | 26.9± 7.4 | 52.5±10.5 | 0.1737 | 302.5±60.5 |
| 50 | 58.7±11.2 | 162.2±20.2 | 220.9±23.1 | 0.2660 | 830.0±86.8 |
| 70 | 176.0±20.0 | 246.8±25.5 | 422.8±32.4 | 0.3264 | 1292.0±99.3 |
| 90 | 150.0±18.7 | 290.6±28.1 | 440.6±33.7 | 0.3472 | 1270.0±97.2 |
| 110 | 116.0±15.6 | 171.5±20.7 | 287.5±25.9 | 0.3264 | 879.0±79.2 |
| 130 | 87.8±14.4 | 118.0±16.4 | 205.8±21.8 | 0.2660 | 773.0±82.0 |
| 150 | 36.4± 8.8 | 29.4± 8.1 | 65.8±11.9 | 0.1737 | 379.0±68.0 |
| 170 | 3.0± 1.2 | 2.0± 1.0 | 5.0± 1.56 | 0.0603 | 83.0±25.9 |

The experimental values obtained here are higher than those predicted by theory, and higher than the experimental value of Barnes. The calculated error (standard deviation) for the authors cross sections given in Table II is 10 percent. This calculated error does not include an error in the electron pair cross section nor in the value for the number of deuterons per molecule. Furthermore, no possible systematic or unknown errors are taken into account. If the second method of correcting for azimuthal distribution were considered a probable eror of 14 percent would be a more realistic value. The values in Table II are 14 percent probable errors.

One picture is of some interest and a reproduction is shown in Fig. 7. Here a photo-disintegration took place in the center of the chamber with the proton shown. The neutron went off in almost the opposite direction and scattered a deuteron in its path. From the measured energy and angle of the proton the neutron has the expected energy and angle within experimental error, (the energy of the neutron being determined by the deuteron). Also the direction of the proton and the initial neutron direction, as defined by the proton and origin of the deuteron, lie in the same plane.

Table III gives the data on the angular distribution of the photo-disintegration protons. These data are plotted in Fig. 8 and as expected, agree with a $\sin^2\theta$ distribution, with perhaps a slight assymetry in the forward direction. For comparison a curve described by Marshall and Guth[13] is included also.

[13] J. F. Marshall and E. Guth, Phys. Rev. 76, 1879 (1949).

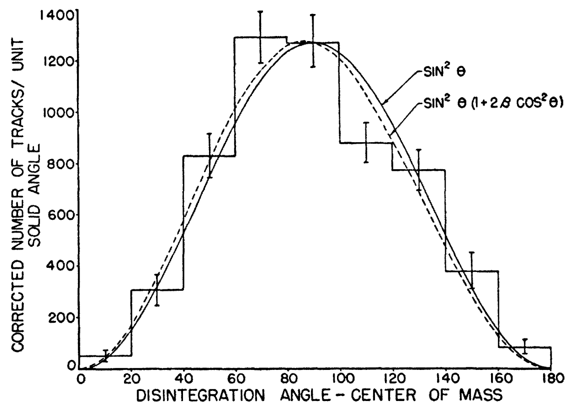



FIG. 8. Histogram of number of tracks corrected for azimuthal geometry, as a function of angle in the center-of-mass system. Also included are curves for $\sin^2\theta$ and the prediction of Marshall and Guth $f(\theta)=(\text{small const.})+\sin^2\theta(1+2\beta\cos^2\theta)$. The difference between the two curves at this energy is too small to allow a clear choice of fit. Both curves are normalized to the experimental number at 90°.

## IX. TRIPLETS

A total of 499 electron triplets were observed during the present experiment. The treatment of these triplets was the same as was used previously.[4] The value of $(Z^2)_{ef}/Z_{ef}$ for this gas is calculated to be 4.31. Having observed a total of 8620 electron pairs, the ratio of the cross section for electron pair production to triplet production results to be

$$\frac{\sigma_p(Z)_{ef}}{\sigma_t(Z^2)_{ef}}=4.01\pm0.12.$$

This compares favorably with the value 3.92±0.26 obtained previously.[4]

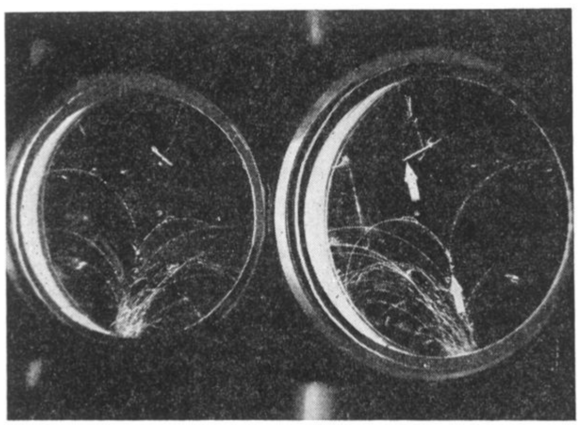
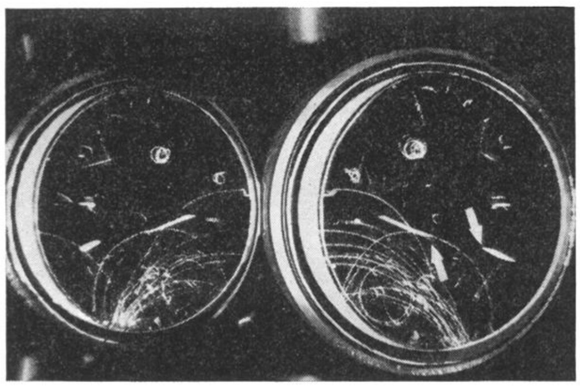
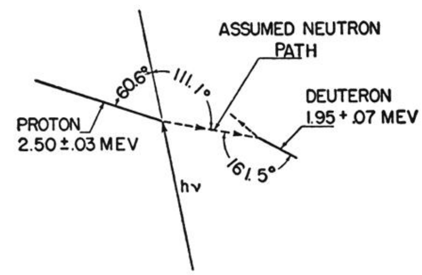


FIG. 4. Stereoscopic cloud chamber pictures showing a photoproton (upper arrow) and a pair (lower arrow) formed in the usable volume of the chamber.



(a)




(b)

FIG. 7. Cloud-chamber picture (a) and schematic diagram (b) showing an $n-d$ scattering by a photo-neutron whose accompanying photo-proton is observable. The proton range and angle show the disintegration to have been caused by a 7.00-Mev gamma-ray. On this basis a deuteron scattered at 18.5° in the laboratory system by the photo-neutron should have 1.85 Mev, which agrees reasonably with the measured value of 1.95±0.07 Mev.