MAY 15, 1941 PHYSICAL REVIEW VOLUME 59

A Photographic Plate Spectrum of the Neutrons from the Disintegration of Lithium by Deuterons

H. T. Richards
The Rice Institute, Houston, Texas

(Received March 31, 1941)

The energy spectrum of the neutrons from $Li+H^2$ has been studied by the photographic emulsion technique. Confirmation is given of the broad 10.8-Mev neutron group reported by Stephens from He recoil data. Reasons are given for believing that not all the neutrons from this group correspond to the 2.8-Mev excitation level in the residual Be^8 nucleus. Evidence is also given for at least two higher (7.5 Mev and 10 Mev) levels in Be^8. A discussion of the photographic emulsion technique is included, and a correction is calculated for the differing probability that long tracks be acceptable for measurement. The stopping power of the emulsion for three different proton energies was found.

Introduction

The energy distribution of neutrons from the disintegration of lithium by deuterons was first measured by Bonner and Brubaker.[1] A rather inhomogeneous distribution was found except for a neutron group at about 14 Mev which was attributed to the formation of Be^8 in its ground state:

$$Li^7+H^2\rightarrow Be^8+n+15.0\text{ Mev.} \tag{1}$$

Bonner and Brubaker's distribution above about 8 Mev was somewhat uncertain because the long range of the recoil protons (~200 cm) required the use of mica sheets to stop them in their high pressure cloud chamber. The correction (to compensate for the unequal probability of observing different length tracks) was large and uncertain when the mica was in the chamber.

By using He instead of H recoils, Stephens[2] was able to obviate the use of mica in the cloud chamber since the range of the recoil alpha-particles is much less than that of the recoil protons. Besides the homogeneous group from (1), he observed another group at about 10.8 Mev which he ascribed to a wide three-Mev excitation level in Be^8:

$$\begin{aligned} Li^7+H^2&\rightarrow {}^*Be^8+n+12\text{ Mev} \\ {}^*Be^8&\rightarrow 2\,He^4+3\text{ Mev.}\end{aligned} \tag{2}$$

In later work Staub and Stephens[3] reported a plateau in the low energy neutron distribution which they attributed to the two-stage disintegration,

$$\begin{aligned} Li^7+H^2&\rightarrow He^5+He^4+14.3\text{ Mev} \\ He^5&\rightarrow He^4+n+0.8\text{ Mev.}\end{aligned} \tag{3}$$

The data of Staub and Stephens[3] above 8 Mev were uncertain since the neutron-helium scattering cross section was not known for this region. At a lower energy (1.1 Mev) an anomaly in this cross section has been discovered.[4] This emphasized the possibility that Stephens' neutron group at 10.8 Mev might be spurious since higher levels in He^5 might give resonance neutron scattering which could be mistaken for true neutron groups.

The object of the present experiment was to make a careful study of this neutron distribution using, however, recoil protons instead of recoil alpha-particles. In this way information could be obtained concerning the reality of the 10.8 Mev group found by Stephens.

Recent work by Powell and others[5] has shown the value of the photographic emulsion technique for studying nuclear processes. New

---

[1] T. W. Bonner and W. M. Brubaker, Phys. Rev. **48**, 742 (1935).

[2] W. E. Stephens, Phys. Rev. **53**, 223 (1938).

[3] H. Staub and W. E. Stephens, Phys. Rev. **55**, 845 (1939).

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

[5] C. F. Powell and G. E. G. Fertel, Nature **144**, 115 (1939); C. F. Powell, Nature **145**, 155 (1940); C. F. Powell, A. N. May, J. Chadwick, and T. G. Pickavance, Nature **145**, 893 (1940); T. R. Wilkins, J. App. Phys. **11**, 35 (1940). For a general discussion, history, and bibliography on the photographic emulsion technique see M. M. Shapiro, Rev. Mod. Phys. **13**, 58 (1941).

emulsions are now available which record individual proton tracks. Neutron energies can therefore be studied by measuring the ranges of the recoil protons which are produced when a neutron collides with a hydrogen nucleus of the emulsion.

For neutron energy studies the emulsion technique has several advantages over the cloud-chamber method. Scattering material can be kept to a much lower minimum, and as the photographic plate is continuously sensitive, the recording of the neutrons requires only a few hours use of the disintegration equipment. Comparable experiments with cloud chambers would tie up the equipment for weeks or months. This advantage in recording the data is partially offset by the longer and more tedious measuring of the tracks with a microscope. For high energy neutrons the emulsion method has the advantage that it is equivalent to a cloud chamber of infinite diameter. Hence it is possible to avoid the uncertainty in the cloud-chamber data which is introduced by joining runs taken with different stopping powers and with different recoil nuclei.

Notes on the Photographic Emulsion Technique

(1) Emulsion used

Although certain commercial process plates are suitable for recording individual alpha-particles, the only emulsion which was found to give really satisfactory recoil proton tracks was the special halftone plate which Ilford, Ltd. (London) coats to order with emulsions up to 100 microns thick. More recently Ilford has been supplying 300 microns thick emulsions without the glass plates. Eastman Kodak Company also reports that they have developed a plate suitable for recording protons.

(2) Exposure arrangement

The x-ray intensity in the observation room of the Rice pressure Van de Graaff generator was low enough that the plates needed to be wrapped only in paper to exclude light. However, a thin aluminum sheet was used between the paper and the emulsion to prevent recording recoil protons which originated from the paper wrapping. This was done to save time in analyzing the plates, for, otherwise, many more tracks have to be examined before one is found which both begins and ends within the emulsion. For exposure the plates were placed 10 cm from the target with the target in the plane of the emulsion so that the neutrons entered the plate tangentially. A thick target of metallic lithium was bombarded by magnetically analyzed 1200-kev deuterons. A bombardment equivalent to 0.6 microampere hours gave a satisfactory number of tracks. Later a LiCl target was used for a second set of plates. This was done to determine the effect of a possible nitrogen contamination of the metallic lithium (see Results).

(3) Processing technique

More than ordinary care should be taken in the processing of the emulsions, for it is important that background fog be kept to a minimum. The 100-micron thickness of the special Ilford emulsions creates special processing problems. A strongly caustic developer (Eastman's D–9, hydroquinone-NaOH) was used to soften the gelatine quickly and thus allow the developer to reach the bottom parts of the thick emulsion. A thorough rinse and immersion in a hardening bath helps condition the gelatine for the prolonged fixation and washing which is required. A 100-micron thick emulsion takes about an hour to clear in a fresh fixing bath.

If the thick emulsions are exposed to dry air after the processing, they tend to crack or to curl up from the edge of the plate and even pull glass lamina off with them. Therefore the developed plates must be kept in a humidor. Application of a film of collodion aids somewhat in preventing this dehydration and cracking. The effect of dehydration on these thick emulsions makes them unsuited for long use in a vacuum.

(4) Viewing and measuring technique

A compound microscope with a well-corrected objective of large numerical aperture is needed for satisfactory examination of the tracks. For short tracks a calibrated eyepiece could be used for measurements. However, a more convenient and accurate measuring arrangement was required since the track lengths of the recoil protons extended up to 10 times the field of view.

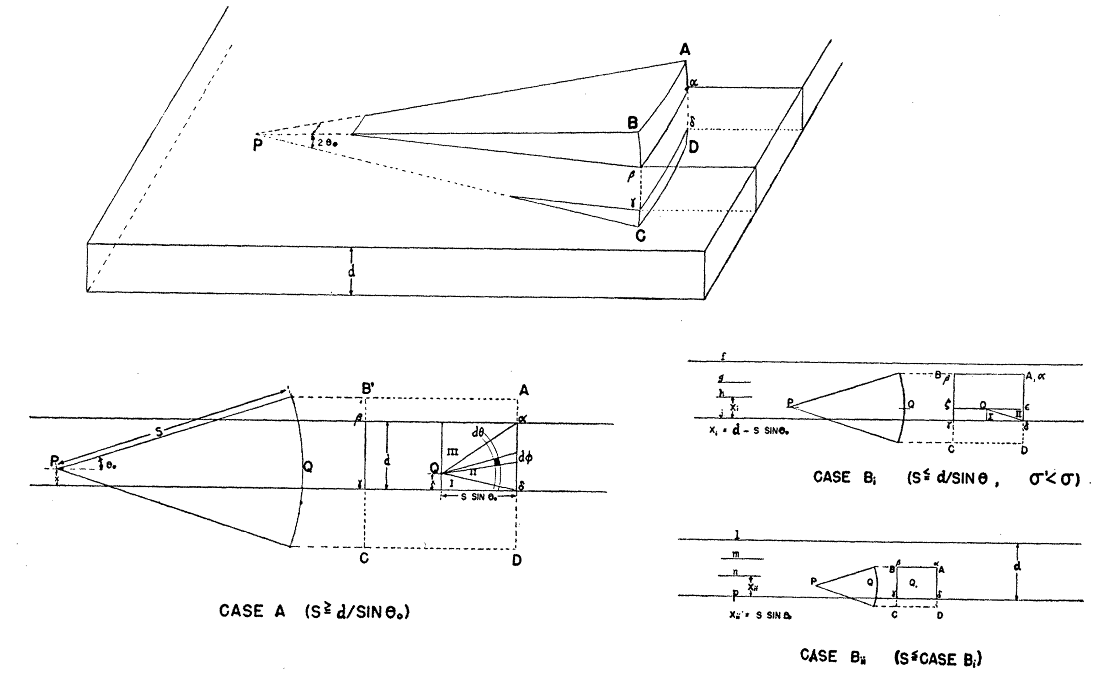

Fig. 1. Diagrams for the calculation of a correction for the differing probability that long tracks end within the emulsion. See text for explanation.

A satisfactory arrangement was made by mounting the focusing equipment and drawtube of a compound microscope upon the bed of a measuring microscope.

A fluorite oil immersion objective (N.A. 1.3; 100×) was used to give a small depth of focus[6] so that a decision could be made as to whether a given track was wholly contained in the emulsion. To give the needed flatness of field two paired 7.5× hyperplane eyepieces were used in a binocular tube attachment. The binocular arrangement is almost a necessity where many measurements are to be made; although the stereoscopic effect is negligible, the saving of eyestrain is quite important.

A mechanical stage reading to 0.1 mm was used to manipulate the plate in the search for measurable tracks. The actual length measurement was accomplished by motion of the measuring microscope bed parallel to the incident neutron direction. As a precaution against remeasuring the same track (important when several are in the field of view) settings of the mechanical stage were used as track coordinates and recorded along with the track length.

Criteria for Measurable Tracks

The most accurate method of measurement of neutron energies by proton recoils is to measure only those tracks which make an angle with the incident neutron beam so small that the recoil proton may be considered as having received the total energy (E_n) of the colliding neutron. Let θ be the angle between the recoil proton and the incident neutron; then the energy (E_p) of the recoil proton is

$$E_p = E_n \cos^2\theta.$$

To insure that the recoil proton gets essentially the neutron's energy, θ was limited to about 12°. Instead of measuring a recoil track only if it were in a cone of half-angle $\theta = 12°$ about the neutron direction, it was found easier to apply the angle criterion for a square pyramid whose half-angle at the vertex was 10°. Thus only tracks scattered into the solid angle subtended by *ABCD* of Fig. 1 satisfy the angle criterion. Crosshairs in the eyepiece were used to test the

---

[6] Measured to be about 4 microns by finding the length in focus at one time for tracks which went completely across the emulsion and hence whose angle could be found.

azimuthal angle in the emulsion plane. Since the microscope's depth of focus was known, the latitude angle to the emulsion plane was easily tested by noting whether a certain minimum track length was in focus at one time.

The other criterion of acceptability of a track for measurement was that the total track length must be wholly contained within the emulsion. This was determined by focusing above and below the endpoints of the track and noting whether there were still background grains in focus. This is where an objective of large numerical aperature is needed to provide a very small depth of focus.

CORRECTION FOR THE DIFFERING PROBABILITY THAT LONG TRACKS BE ACCEPTABLE FOR MEASUREMENT

Because of the finite thickness of the emulsion, it is evident (Fig. 1) that, for a given latitude angle, many more of the short than the long tracks will end within the emulsion. Hence in order to get the correct relative number of short and long tracks it becomes necessary to apply a correction for this differing probability that a long track be acceptable for measurement.

Consider the protons scattered from some point P at a distance x from the bottom of the emulsion. Let $d\sigma$ = number of protons scattered per solid angle $d\omega$, θ_0 = maximum azimuthal and maximum latitude angle which a recoil proton can make and still be acceptable for measurement, S = track length of the recoil proton, and d = emulsion thickness. Also let σ and σ' be the number of protons of given S which are scattered from P into the solid angle subtended by $ABCD$ and $\alpha\beta\gamma\delta$, respectively (Fig. 1). Consider a single recoil proton of σ. Then the probability (W) that it will also end within the emulsion (and hence be acceptable for measurement) is

$$W=\sigma'/\sigma.$$

σ is calculated upon the assumption that the scattering is spherically symmetric in the center of gravity coordinates. In laboratory coordinates this becomes

$$d\sigma=2k\sin\theta\cos\theta d\theta d\phi$$

and as θ_0 is small

$$\sigma=8\int_0^{\pi/4}\int_0^{\theta'}2k\sin\theta\cos\theta d\theta d\phi=8k\sin^2\theta_0,$$

since $\sin\theta'=\sin\theta_0\sec\phi$.

For the calculation of σ' two different ranges of track lengths must be considered:

Case A:

$S\geqq d/\sin\theta_0$. For this length S there are no tracks with latitude angle greater than θ_0 which are wholly recorded in the emulsion. σ' then turns out to be independent of the position of the scattering center P. From Fig. 1 it is seen that

$$\sigma'=2\left(\int_{\phi_{\text{II}}}^{\pi}\int_0^{\theta_{\text{III}}}+\int_{\phi_{\text{I}}}^{\phi_{\text{II}}}\int_0^{\theta_{\text{II}}}+\int_0^{\phi_{\text{I}}}\int_0^{\theta_{\text{I}}}\right)2k \times\sin\theta\cos\theta d\theta d\phi$$

$$=4k(d/S)\sin\theta_0,$$

since

$$\sin\theta_{\text{I}}=(x/S)\sec\phi$$
$$\sin\theta_{\text{II}}=\sin\theta_0\sec\phi$$
$$\sin\theta_{\text{III}}=[(x-d)/S]\sec\phi$$
$$\tan\phi_{\text{I}}=(S/x)\sin\theta_0$$
$$\tan\phi_{\text{II}}=[S/(x-d)]\sin\theta_0.$$

Hence

$$W_A=\sigma'/\sigma=d/(2S\sin\theta_0)$$

when

$$S\geqq d/\sin\theta_0.$$

Case B:

$S\leqq d/\sin\theta_0$. Here σ' is dependent upon the position of the scattering center P. However, upon averaging over all positions the final result is

$$W_B=1-(S\sin\theta_0)/2d$$

when

$$S\leqq d/\sin\theta_0.$$

In obtaining the above expression two subcases (i) and (ii) are considered:

(i) $S\leqq d/\sin\theta_0$ but of sufficient length that $\sigma'<\sigma$ for all possible positions of P. Let g and h (Fig. 1, case B_i) be at distance $x_i=d-S\sin\theta_0$ from the surfaces of the emulsion. Hence when P is interior to gh, i.e., $x_i\leqq x\leqq(d-x_i)$, the acceptance probability W_{gh} is the same as in case A, i.e., $W_{gh}=W_A$. The acceptance proba-

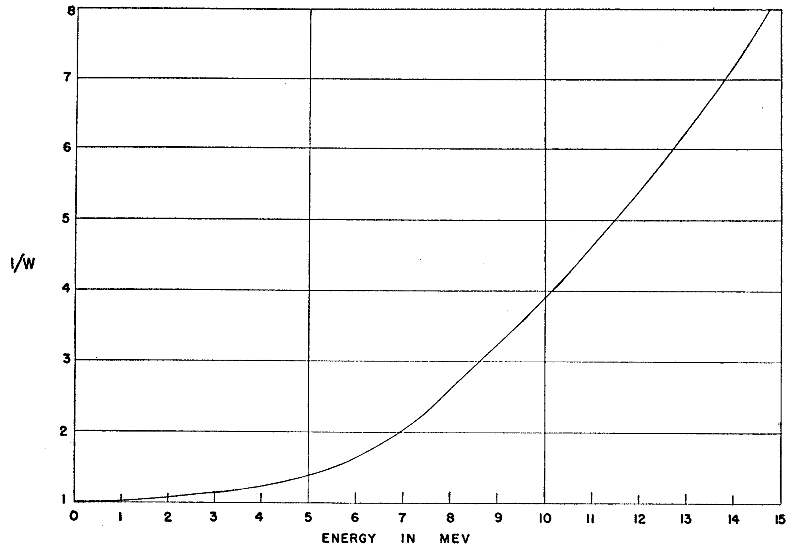

FIG. 2. Variation of the correction factor $(1/W)$ with energy of the recoil proton. W is the probability that a recoil proton of given energy and scattered from P into solid angle subtended by $ABCD$ (Fig. 1) will end within the emulsion.

bility W_{hj} (for $x<x_i$) then remains to be calculated and averaged with W_{gh}. From Fig. 1, case B_i, it is seen that for $x<x_i$, $\sigma'=(\sigma/2)+\sigma''$ where σ'' is the number of protons scattered from P into the solid angle subtended by $\gamma\delta\epsilon\zeta$. Hence

$$\sigma''=2\left(\int_{\phi_{\mathrm{I}}}^{\pi/2}\int_0^{\theta_{\mathrm{II}}}+\int_0^{\phi_{\mathrm{I}}}\int_0^{\theta_{\mathrm{I}}}\right)2k\sin\theta\cos\theta d\theta d\phi$$
$$=4k(x/S)\sin\theta_0.$$

Thus the average value $\langle W_{hj}\rangle_{\mathrm{Av}}$ for $0\leqq x\leqq x_i$ is

$$\langle W_{hj}\rangle_{\mathrm{Av}}=\sigma'/\sigma=\tfrac{1}{2}+x_i/(4S\sin\theta_0).$$

Hence the final average for all possible positions of P: $0\leqq x\leqq(d/2)$ is

$$W_B=(2/d)[x_i\langle W_{hj}\rangle_{\mathrm{Av}}+(d/2-x_i)W_A]$$
$$=1-(S\sin\theta_0)/2d.$$

(ii) All tracks shorter than case B_i. From Fig. 1, case B_{ii}, $x_{ii}=S\sin\theta_0$ and hence for $x_{ii}\leqq x\leqq(d/2)$ then $\sigma'=\sigma$ and therefore $W_{mn}=1$. For $x<x_{ii}$ then $\sigma'<\sigma$ and hence the correction is that calculated in (i) for $\langle W_{hj}\rangle_{\mathrm{Av}}$ except that the expression is averaged between 0 and x_{ii} instead of 0 and x_i. This gives

$$\langle W_{np}\rangle_{\mathrm{Av}}=(\tfrac{1}{2})+x_{ii}/(4S\sin\theta_0)$$

and thus the final average over $0\leqq x\leqq(d/2)$ yields

$$W_B=(2/d)[x_{ii}\langle W_{np}\rangle_{\mathrm{Av}}+(d/2-x_{ii})W_{mn}]$$
$$=1-(S\sin\theta_0)/2d,$$

which is the same average value as found in (i).

For convenience in applying this correction to the observed distribution, $1/W$ was plotted against the recoil proton energy instead of range (S). The effective emulsion thickness (d) was measured to be 80 microns. Figure 2 shows the correction curve for this value of d and for $\sin\theta_0=0.2$.

RESULTS

About 3500 acceptable tracks have been measured and are recorded in 0.4-Mev energy intervals (curve *I*, Fig. 3). 900 of those tracks (plotted separately in Fig. 4) were from the plates exposed to the LiCl target instead of the metallic lithium one. This was done to decide whether the neutron group at 5 Mev (curve *II* Fig. 3) could be from the disintegration[7]

$$N^{14}+H^2\rightarrow O^{15}+n+5.1\text{ Mev},$$

since a black layer of Li_3N appears to form on the surface of a freshly prepared metallic lithium target.[8] That this cannot account for this neutron group is shown by the appearance of the same group on the data taken with the LiCl target. (The number of neutrons from Cl at this bombarding voltage is negligible.)

---

[7] W. E. Stephens, K. Djanab, and T. W. Bonner, Phys. Rev. **52**, 1079 (1937).

[8] W. G. Shepherd, R. O. Haxby and E. L. Hill, Phys. Rev. **52**, 675 (1937).

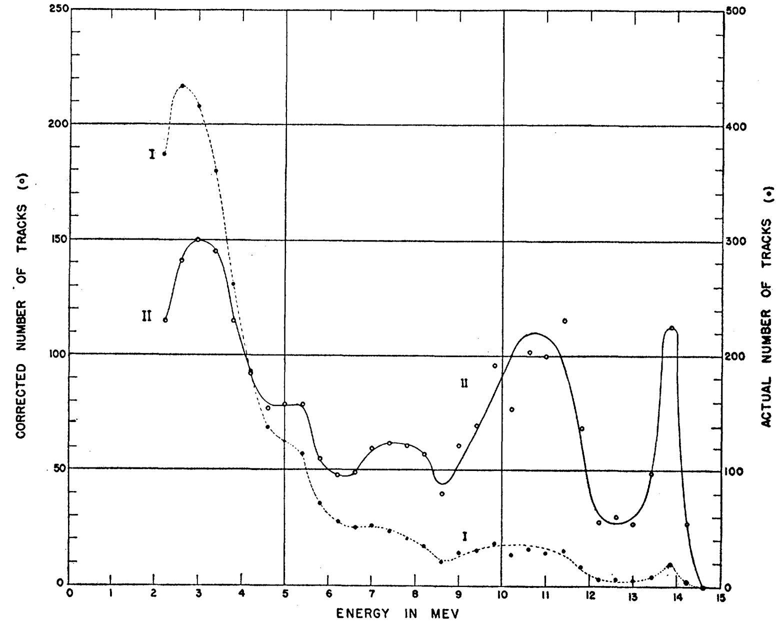

FIG. 3. Total data from plates exposed at 90° to lithium targets which were bombarded by 1200-kv deuterons. Curve *I* gives the measured distribution of recoil protons. Curve *II* gives the inferred neutron distribution obtained after the correction of Fig. 2 and the correction for scattering cross section had been made to the recoil proton data.

CALIBRATION OF PLATES

The stopping power of the emulsion for two different proton energies was found by the use of the monochromatic neutrons from the *d–d* reaction* (Fig. 5). A 20-kv thick heavy paraffin target was bombarded by 700-kv deuterons. Plates were placed 12 cm from the target at 0° and 90° to the incident beam. From about 200 tracks measured on each plate, a mean range of 135 microns and 72 microns was found for the plates placed at 0° and 90°, respectively. Since recoils up to 12° were measured, this mean recoil proton range corresponds to an energy $\frac{1}{2}E_n\theta_0^2$ less[9] than the calculated neutron energy from Bonner's precise determination of $Q=3.31$ Mev.[10] Thus the corresponding recoil proton energies on the plates at 0° and 90° are calculated to be 3.73 Mev and 2.60 Mev, respectively. This gives a stopping power of 6.6 microns per cm of air for the 3.73-Mev protons and 6.5 microns per cm of air for the 2.60-Mev protons. This indicated that the stopping power relative to air might decrease slightly with increasing proton energies. Hence a calibration point for a high proton energy was desired. This was obtained from the mean range (1415 microns) of the longest range recoil protons produced by the neutrons from the disintegration of lithium by deuterons. The reaction producing these neutrons is known to have a $Q=15.0$ Mev.[2, 3] Hence the mean range of this recoil proton group should correspond to an energy of $14.1-\frac{1}{2}E_n\theta_0^2=13.8$ Mev since recoils with an angle up to $\theta_0=12°$ were measured. This gives a stopping power of 6.9 microns per cm of air for the 13.8-Mev protons. A smooth curve through these three values of the stopping power was taken to represent the variation of stopping power with energy.

The range number curves were transformed into energy number curves by the use of the 1938 Cornell range-energy relations. Curve *I*, Figs. 3 and 4, gives the measured recoil proton distribution. Curve *II* of the same figures represents the inferred neutron distribution obtained by correcting the recoil proton distribution for geometry (different probability of long tracks being acceptable) and for the variation of the neutron-proton scattering cross section with energy.[11]

---

* Dr. E. Hudspeth aided in measuring the plates exposed to the *d–d* neutrons. A preliminary report has already been published: H. T. Richards, and E. Hudspeth, Phys. Rev. **58**, 382 (1940).

[9] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 290 (1937).

[10] T. W. Bonner, Phys. Rev. **59**, 237 (1941).

[11] Wigner's formula was used: $\sigma^a=k[\frac{1}{4}(\epsilon_1+E/2)^{-1}+\frac{3}{4}(\epsilon_2+E/2)^{-1}]$ where $\epsilon_1=0.12$ Mev and $\epsilon_2=2.18$ Mev. E is the neutron energy. [Rev. Mod. Phys. **8**, 117 (1936).]

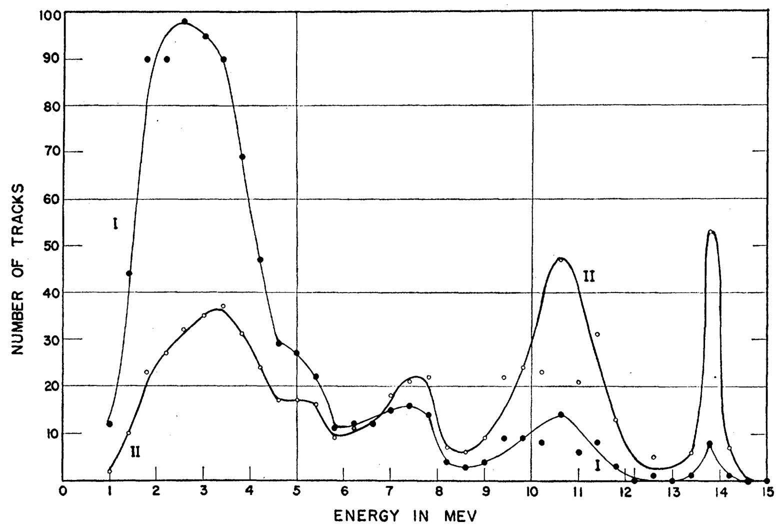

Fig. 4. Similar to Fig. 3 except that these data are only from the plates exposed to the LiCl target. This shows that the neutron group at 5 Mev of Fig. 3 was not due to the disintegration of the nitrogen of the Li_3N which appeared to form on the surface of the metallic lithium target used for the bulk of the data on Fig. 3.

Discussion of Results

Neutrons of 3.5 Mev are the highest energy ones that could be produced from the disintegration of the Li^6 isotope by 1200-kev deuterons:[12]

$$Li^6+H^2\rightarrow Be^7+n+3.3\text{ Mev} \quad (4)$$

$$Be^7+e_k\rightarrow Li^7+\eta+0.87\text{ Mev.}$$

Furthermore, reaction (3) can only give neutrons of less than 4-Mev energy. Hence all the neutrons above 4 Mev must be from reaction (1) and from the following modes of disintegration of the Li^7 isotope:

$$Li^7+H^2\rightarrow He^4+He^4+n+15.1\text{ Mev,} \quad (5)$$

$$Li^7+H^2\rightarrow {}^*Be^8+n+Q_6, \quad (6)$$

$${}^*Be^8\rightarrow 2\ He^4+Q_7. \quad (7)$$

Reaction (5) is certainly not the favored mode of disintegration since a three-particle disintegration cannot give the observed homogeneous neutron groups at 5 Mev, 7.5 Mev, 10.8 Mev, and 14 Mev (Figs. 3 and 4). Therefore these neutron groups are assigned to reaction (1) and to reaction (6) where Be^8 may be formed in various excited states.

The rather sharp 14-Mev neutron group (first reported by Bonner and Brubaker[1]) then corresponds to the formation of Be^8 in the ground state which (according to Wheeler's recent analysis[13] of other experiments) is a 100-ev wide $^1S_0$ level about 125 kev unstable against alpha-particle emission. Hence the observed 0.5-Mev half-width of the neutron group may be considered as experimental[14] rather than real width.

The wide neutron group at about 10.8 Mev is similar to that reported by Stephens[2] from his study of recoil alpha-particles in a cloud chamber. This equivalence of the alpha-particle and proton recoil data shows that there are no excited levels of He^5 in this region which give resonance neutron scattering.

This neutron group at 10.8 Mev has previously[3] been identified with the 2.8-Mev level in Be^8 which has been observed in boron disintegrations.[15] However, the observed half-width of this neutron group (Figs. 3 and 4) is at least 2 Mev. On the assumption that the half-width of the 14-Mev group is experimental, then the natural width of the Be^8 level associated with the 10.8-Mev neutron group would be at least[16]

$$(9/8)(2.0-0.5)=1.7\text{ Mev.}$$

---

[12] This Q value is calculated from the mass of Be^7 given by Haxby, Shoupp, Stephens and Wells, Phys. Rev. **58**, 1035 (1940).

[13] J. A. Wheeler, Phys. Rev. **59**, 27 (1941).

[14] A recent determination in this laboratory of the excitation function for this disintegration indicates that the use of a thick target should in itself produce a 0.3-Mev experimental width to the neutron group.

[15] Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **150**, 241 (1935); P. I. Dee and C. W. Gilbert, Proc. Roy. Soc. **154**, 279 (1936); J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **154**, 246 (1936).

[16] $\delta Q=(M/M_3)\delta E_2{}^0$, from (770*b*), page 277 of reference 9.

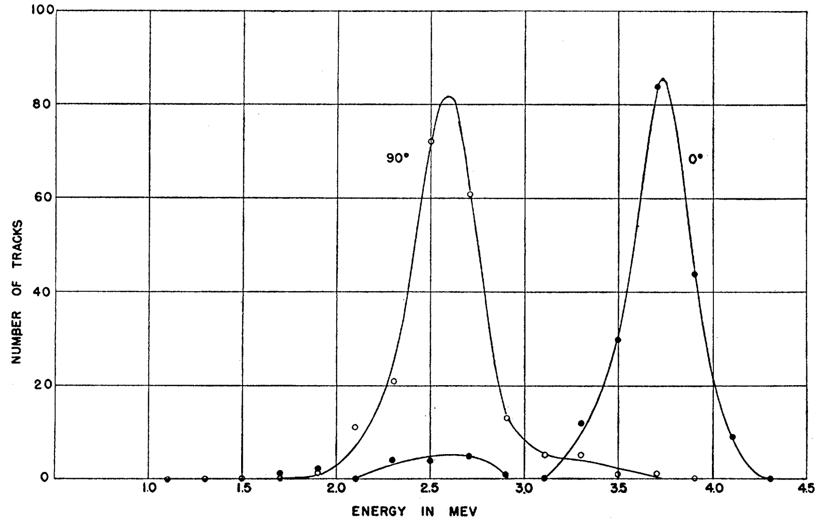

FIG. 5. The *d–d* neutron spectrum used for the calibration of the stopping power of the plates. The plates were placed at 90° and 0° to a 700 kv bombarding beam. Since a thin target was used, these data also give an indication of the resolving power of the emulsion method. (For interpretation of the high energy tail on the 90° data and the group at 2.5 Mev on the 0° data see Richards and Hudspeth, Phys. Rev. **58**, 382 (1940).)

This is over twice the 0.8-Mev width of the 2.8-Mev level of Be^8 which is observed in boron disintegrations.[15] Furthermore, the peak of the recoil protons from neutrons associated with a 2.8-Mev level in Be^8 is calculated to come at $11.6-(\frac{1}{2})E_n\theta_0^2=11.4$ Mev.[9] This is about 0.6 Mev higher than the 10.8-Mev observed peak (Figs. 3 and 4). Thus it would seem that not all of the neutrons in this group correspond to the 2.8-Mev level in Be^8. The existence of another level in Be^8 at about 4 to 5 Mev would account for the remaining neutrons in this group and also explain its apparent width. Independent evidence for such a level is given by the recent discovery in this laboratory[17] of a fairly intense 4.9-Mev gamma-ray from deuteron bombardment of Li^7. This gamma-ray follows the same excitation function as the neutrons and so it may be supposed to result from a 4.9-Mev excitation level which has odd angular momentum and/or odd parity so that the ordinary breakup into two alpha-particles is prohibited. A selection rule depending on this odd angular momentum and/or parity might then explain why this level is not observed in the boron disintegrations when the intermediate C^{12} nucleus breaks up into Be^8 and He^4.

The next lowest neutron group ($\sim$7.5 Mev) has a real half-width of probably about 1.5 Mev. Hence it requires a 7.5-Mev excitation level in Be^8 which would be about 1.7 Mev wide. From the alpha-particles of the $B^{10}+H^2$ disintegration Smith and Murrell[18] infer a similar level in Be^8 although perhaps not quite so wide.

The neutron group at 5 Mev (only partially resolved) must be associated with a wide 10-Mev level in Be^8. Estimates of its width are quite uncertain since it is only partially resolved. However, it appears to be about as wide as the 7.5-Mev group. This group at 5 Mev is not inconsistent with Staub and Stephens' neutron distribution[3] from alpha-particle recoils although they drew their published curve through the proton-recoil points because of the uncertainty in the neutron alpha-particle scattering cross section. Since the present data remove this uncertainty it might be expected that their data with the He recoils would be the more reliable since their geometrical correction is quite small for the He recoils in this region.

The present data show no plateau in the region 0.8–3.9 Mev which could be ascribed to neutrons from the two-stage reaction (3) though part of the sharp rise at about 4 Mev may be from this source. However Rumbaugh, Roberts, and Hafstad[19] found that for 800-kev deuterons about 8 percent of all neutrons are from the Li^6 isotope. Since these are all confined to the

---

[17] Bennett, Bonner, Richards and Watt, Letter to the Editor, Phys. Rev., to be published.

[18] C. L. Smith and E. B. M. Murrell, Proc. Camb. Phil. Soc. **35**, 298 (1939).

[19] Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938).

lower energy portion of the curve, we may expect that about a fourth of the neutrons with energy less than 3.5 Mev are from the Li^6 isotope. Hence, unless reaction (3) is the predominantly favored mode of disintegration in this region, the neutrons from Li^6 and reaction (6) would be sufficient to obscure such a plateau. This would certainly be the case if the relative frequency of reaction (3) to reactions (5)+(7) were about 1 : 100 as Williams, Shepherd and Haxby[20] report from their studies of the alpha-particles from the above reactions.

It is uncertain whether the peak at 3 Mev is from the formation of a still more highly excited Be^8 or whether it is from the Li^6 disintegration in which Be^7 is formed, reaction (4). Other modes of disintegration of the Li^6 isotope are:

$$Li^6+H^2\rightarrow He^4+He^3+n+1.6\text{ Mev}$$
$$Li^6+H^2\rightarrow He^5+He^3+0.8\text{ Mev}$$
$$He^5\rightarrow He^4+n+0.8\text{ Mev.}$$

For 1200-kev deuterons neither of these reactions yields neutrons of over 2 Mev. Hence curve *II*, Fig. 4, indicates that these are not prolific reactions.

Nevertheless, the interpretation of the spectrum below 3.5 Mev remains ambiguous until a careful study is made of the neutrons from a target of the separated Li^6 isotope.†

ACKNOWLEDGMENTS

It is a pleasure to thank Dr. T. W. Bonner for his suggestion of the problem, his aid in exposing the plates, and his helpful discussion of the results.

---

[20] Williams, Shepherd and Haxby, Phys. Rev. **52**, 390 (1937).

† Rumbaugh, Roberts and Hafstad, reference 19, have made a rough measurement of this neutron distribution.

MAY 15, 1941 PHYSICAL REVIEW VOLUME 59

Deuteron Disintegration by Electrons

B. PETERS AND C. RICHMAN
Department of Physics, University of California, Berkeley, California

(Received March 14, 1941)

The cross section for the disintegration of deuterons by electrons has been calculated. Near the threshold the "magnetic" cross section is larger, increasing with the square while the "electric" cross section increases with the cube of the energy. They become equal at about 600 kev above the threshold when each has a value of 3.5×10^{-31} cm². The disintegration neutrons should be observable from 50 kev up. An experiment of this kind might therefore be used to check the theoretically predicted *magnetic* disintegration. This seems desirable since a parallel effect for photo-disintegration has so far not been observed.

THE electron currents and voltages which have recently been obtained[1] with electrostatic generators make it appear probable that the disintegration of deuterons by electrons can be observed. For the present such experiments will have to be confined to electron energies only slightly in excess of the deuteron binding energy.

As in photo-disintegration, the only appreciable transition probabilities are those to the ^3P and ^1S states of the disintegrated deuteron. The corresponding cross sections are usually referred to as "electric" and "magnetic," respectively. The theory predicts, both for photo- and electron-disintegration, a predominance of the magnetic transition and corresponding spherically symmetric distribution of the emitted particles, for energies just above the threshold. Protons and neutrons ejected in the direction of the incident gamma-ray have been looked for but have not been found. Measurements were made with 2.62-Mev gamma-rays by J. Chadwick, N. Feather and E. Bretscher[2] and also by H. v. Halban.[3] No evidence for magnetic disintegration was found. V. Halban puts the ratio of magnetic to electric

---

[1] D. L. Northrup, L. C. van Atta, R. J. Van de Graaf, J. S. Clark and C. M. van Atta, Phys. Rev. **57**, 563 (1940) and Phys. Rev. **58**, 199 (1940).

[2] J. Chadwick, N. Feather and E. Bretscher, Proc. Roy. Soc. **A163**, 366 (1937).

[3] H. v. Halban, Nature **141**, 644 (1938).