A Study of the Breakup of Li^8 *

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(Received January 2, 1948)

An experimental technique in which radioactive Li^8 atoms are introduced into the gas of a cloud chamber has been used to determine the energy distribution of the alpha-particles from the Li^8 breakup. The maximum of the distribution occurs at 3.3 Mev and the width of half-intensity is 1.2±0.2 Mev. The theoretical distribution

$$N_\alpha dE_\alpha = [P_{\alpha J}(Q-2E_\alpha)^5/(E_0-2E_\alpha)^2+\tfrac{1}{4}\Gamma^2]dE_\alpha$$

with $E_0=3.1$ Mev, $\Gamma=0.8$ Mev, and $J=4$, gives good agreement with experimental data. N_α is the relative number of alpha-particle pairs, E_α is the energy of one alpha-particle, $P_{\alpha J}$ is the penetrability of one alpha-particle from a Be^8 nucleus having J units of total angular momentum, and E_0 and Γ are, respectively, the mean energy and width at half-intensity of the excited level in Be^8. No evidence was found for a short-range group of alpha-particles which would correspond to the disintegration energy of the ground state of Be^8.

1. INTRODUCTION

RADIOACTIVE Li^8 was discovered by Crane, Delsasso, Fowler, and Lauritsen[1] by the observation of a short-period beta-ray activity produced by deuteron bombardment of lithium. The period of the delayed beta-particles has been measured accurately by Lewis, Burcham, and Chang[2] and found to be 0.88 sec. They also found delayed alpha-particles having a decay period of 0.88 sec. These activities result from the following reactions:

$$Li^7+H^2\rightarrow Li^8+H^1-0.26 \text{ Mev}, \quad (1)$$

$$Li^8\rightarrow He^4+He^4+e^-+\nu+16.0 \text{ Mev}. \quad (2)$$

In the excitation curve for reaction (1) in which Li^8 is produced, there are resonances at 0.65, 1.02, and 1.35 Mev.[3] The energy limit of the beta-ray spectrum has been found to be about 12.0 Mev.[4]

The exact process by means of which Li^8 decays into two alpha-particles and an electron is not known, but it is generally considered that the emission of the electron leaves a highly unstable Be^8 nucleus. Study by means of a mass spectrograph[5] has shown that the relative abundance of Be^8 in natural beryllium is less than 10^{-5}. Wheeler[6] concludes, upon consideration of the experiments of Laaff[7] and Fink,[8] that Be^8 is unstable with respect to two alpha-particles by about 125±25 kev.

In an attempt to determine the mechanism of the decay of Li^8 several investigators[2, 9–13] have studied the energy distribution of the alpha-particles. Widely varying energy distributions have been found. Gamow and Teller[10, 13] have derived an expression for the energy distribution of the alpha-particles to be expected if the breakup of Li^8 is a 4-body disintegration. Their expression is based on the Fermi theory of beta-neutrino decay and assumes that the two alpha-particles break apart at the same time the beta-particle and neutrino are emitted. The Gamow-Teller expression is as follows:

$$N_\alpha dE_\alpha = (Q-2E_\alpha)^5 E^{J+\frac{1}{2}} dE_\alpha, \quad (3)$$

where N_α is the relative number of alpha-

* A preliminary report of these results was made at the May, 1947 meeting of the American Physical Society [Phys. Rev. **72**, 163 (1947)].

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[2] Lewis, Burcham, and Chang, Nature **139**, 24 (1937).

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[7] O. Laaff, Ann. d. Physik **32**, 745 (1938).

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[9] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **51**, 1103 (1937).

[10] Rumbaugh, Roberts, and Hafstad, Phys. Rev. **51**, 1106 (1937).

[11] Smith and Chang, Proc. Roy. Soc. **A166**, 415 (1938).

[12] Bennett, Bonner, Mandeville, and Watt, unpublished data.

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

particle pairs per unit energy range, Q is the total energy available for the disintegration, E_α is the energy of one alpha-particle, and J is the total angular momentum of the Be^8 nucleus. Wheeler[6] has developed a theory which gives the energy distribution of the alpha-particles which would be expected if the disintegration were a three-body disintegration. He assumes that the mechanism is the beta-neutrino decay of Li^8 according to the Fermi theory, followed almost immediately by the breakup of an excited state of Be^8 into two alpha-particles. The distribution is given by the following expression:

$$N_\alpha dE_\alpha = \frac{(Q-2E_\alpha)^5}{(E_0-2E_\alpha)^2+\frac{1}{4}\Gamma^2} dE_\alpha, \qquad (4)$$

where E_0 and Γ are, respectively, the mean energy and the width at half-intensity of the excited level in Be^8.

Lewis, Burcham, and Chang[2] found a continuous energy distribution of alpha-particles with combined energies as great as 12 Mev. As a matter of convenience, throughout the remainder of this paper we shall always refer to the combined energies of the two alpha-particles from the breakup of Li^8. Fowler and Lauritsen[9] found a maximum in the distribution curve at 2.6 Mev and a corrected width of about 1.0 Mev. Using counter techniques, Rumbaugh, Roberts, and Hafstad[13] found no maximum; however, using a cloud chamber, they found a maximum in the curve at 2.6 Mev. Smith and Chang,[11] using counter techniques, studied the energy distribution of the alpha-particles from 2.4 Mev up to the end point of 15.5±0.1 Mev and found no maximum in the distribution curve. Bennett, Bonner, Mandeville, and Watt[12] found a maximum in the distribution curve of 2.0 Mev. At the conclusion of their experimental work, however, it was discovered that they, and most of the previous investigators, had neglected to take into account the alpha-particle range correction due to the recoil of the Li^8 nuclei into the target. The failure to make this correction would cause the maximum of the distribution to occur at too low an energy value. Since the range energy relations for lithium nuclei are not known accurately, it was impossible to evaluate the exact amount of this effect. However, they did suggest a way to obviate this difficulty. The experimental arrangement used in the experiment to be described here was based on these suggestions. The experiment to be described was undertaken for the purpose of determining accurately this energy distribution curve of the alpha-particles from 0 up to about 5 Mev. It was also hoped that some pictures showing all three observable disintegration particles of the breakup of Li^8 atoms would be obtained. Analysis of such pictures could determine whether or not the neutrino hypothesis is necessary to conserve momentum in radioactive beta-decay.

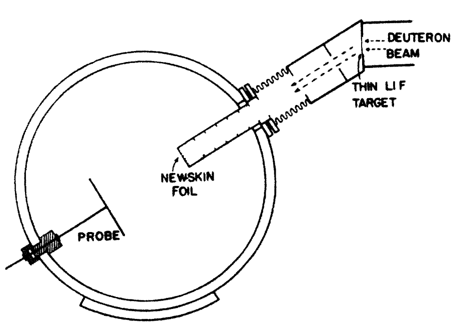


FIG. 1. Experimental arrangement of the cloud chamber and target holder. Some of the radioactive Li^8 atoms recoil from the LiF target and proceed along the evacuated tube in the direction of the arrows through the thin foil into the cloud chamber.

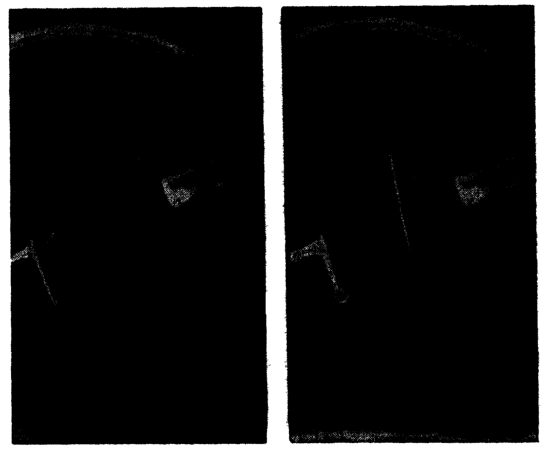
2. EXPERIMENTAL ARRANGEMENTS

The deuterons were accelerated to an energy of 1.3 Mev by means of the Rice Institute pressure Van de Graaff generator. The atomic beam was deflected through an angle of 90° by an annular ring-type magnetic energy selector. Targets were prepared by evaporating from a hot tungsten filament in a high vacuum about 0.2 mg/cm² of LiF on to an aluminum foil which weighed 0.22 mg/cm.² The foil was supported on an aluminum disk into which there had been cut a rectangular window 1 cm by 2 cm. This was mounted so that the incident deuterons penetrated the aluminum foil before reaching the deposit of LiF. Some of the Li^8 atoms formed had sufficient recoil energy and the correct direction to pass through a new-skin foil into the gas of a cloud chamber.

The cloud chamber used was 26 cm in diameter and 11 cm in depth. In order to keep nuclear scattering down to a low value, helium and water vapor were used. A pressure of 1.7 atmospheres was used in an effort to render visible as many of the beta-rays as possible. Figure 1 shows the experimental arrangement of the cloud chamber and target holder used.

In order to keep the direct deuteron beam out of the cloud chamber, the cloud-chamber port was located at an angle with respect to the beam. Momentum considerations allow Li^8 atoms to recoil within a maximum angle of 35° for a bombarding energy of 1.3 Mev. In the early part of the experiment the cloud chamber was placed so that some Li^8 atoms, recoiling at an angle of 20° from the forward direction of the incident deuterons, would pass through the new-skin foil into the cloud chamber. Later the angle was changed to 30° in order to reduce, by a factor of 5, the Coulomb scattering of the incident deuterons by the target. Even with this improvement, the Coulomb scattering of the deuterons was a major problem. In the region directly in front of the new-skin foil, and out for a distance of about 4 cm, a fog was formed on nearly every expansion. Tracks, due to the breakup of Li^8 atoms late in the sensitive period of the chamber, sometimes had gaps of one to two cm in length in this region. Electron tracks were, for all practical purposes, completely obscured in this region. Alpha-particles from the decay of Li^8 atoms which had come to rest on the walls of the vacuum system between the target and the new-skin foil were prevented from getting into the cloud chamber by means of thin brass baffles shown in Fig. 1.

New-skin foils, which had stopping powers from 0.5 mm to 0.7 mm of air, were used. They were mounted on well-polished silver-plated microphone screen which had 20 percent of its area open and was 0.015 cm thick. In preliminary experiments it was found that the recoil ranges of the Li^8 atoms, after penetration of the new-skin foil, were generally not more than 1 cm out into the cloud chamber. Some of these Li^8 atoms moved approximately 1 cm farther out into the cloud chamber because of gaseous diffusion during the 1-second time interval between the short bombardment period and the expansion of the cloud chamber. There was a pronounced bunching of the tracks near the foil which was very undesirable. It was found that by means of



(a) (b)

FIG. 2. Representative cloud-chamber photographs for the breakup of Li^8. The bright object at the right of each picture is the collimating tube through which the Li^8 atoms enter the cloud chamber. The bright T-shaped object on the left is the electrostatic probe which pulls the Li^8 ions toward the center of the cloud chamber. The alpha-particle tracks near the probe are from the breakup of Li^8 atoms which have been pulled to the probe. (a) Photograph of an alpha-particle pair having a combined energy of about 3.5 Mev. The angular deviation between the paths of the two alpha-particles is 8.5°. (b) Photograph showing two alpha-particle pairs. Each pair has a combined energy of about 4 Mev, and the angular deviation between the paths of the two alpha-particles of a pair is about 2° for both of the pairs.

an electrostatic probe, as shown in Fig. 1, some of the Li^8 ions could be pulled into the central region of the cloud chamber. A potential of 500 volts on the probe, with an accompanying 250 volts on the top and bottom of the cloud chamber, was sufficient to pull some of the Li^8 ions over to the probe; a considerable fraction of the Li^8 ions getting through the foil disintegrated near the center of the cloud chamber.

3. PROCEDURE

The operation of the cloud chamber and associated equipment was entirely automatic. The target was bombarded for a period of about 0.5 sec. During this time there was a strong horizontal pulling-out field. At the end of the bombarding period the horizontal field was turned off and the vertical clearing field was turned on again.

In the early stages of the experiment considerable difficulty was experienced with electron tracks produced by x-rays from the Van de Graaff generator. A chance coincidence of one of these electron tracks and a Be^8 breakup might be misinterpreted as an electron from the decay of a Li^8 nucleus. Later on in the experiment the x-radiation was eliminated by turning off the ion source before the cloud chamber was expanded. This procedure also eliminated neutron recoils, which would otherwise be accepted as short alpha-particle tracks. The electron accelerating voltage in the ion source was turned off by a relay controlled by a photo-cell. The photo-cell was activated by an auto headlight unit located at one end of the pressure tank of the Van de Graaff generator.

In the analysis of the reprojected alpha-particle tracks only sharp tracks, whose directions were within 30° of a line drawn perpendicular to the plane of the stereoscopic system, were measured. Also, only those tracks whose centers (points of origin) were between the foil and the electrostatic probe were used. Tracks which had gaps of 1 cm or more where they had passed through a "foggy" region, were also rejected.

4. RESULTS

Four hundred and twenty-six tracks were measured, and in a large fraction of the cases, the two oppositely directed alpha-particle tracks were collinear within a few degrees. However, angles up to 10° were observed. No evidence was found that the two oppositely directed alpha-particles might have different energies. We observed no unmistakable electrons tracks starting in the gas at the midpoint of the alpha-particle tracks. However, several modifications of the equipment can be made which will increase the probability of observing such events. Representative cloud-chamber photographs are shown in Fig. 2.

The combined ranges of the two alpha-particles were divided by two in order to get the ranges of the single alpha-particles. These ranges

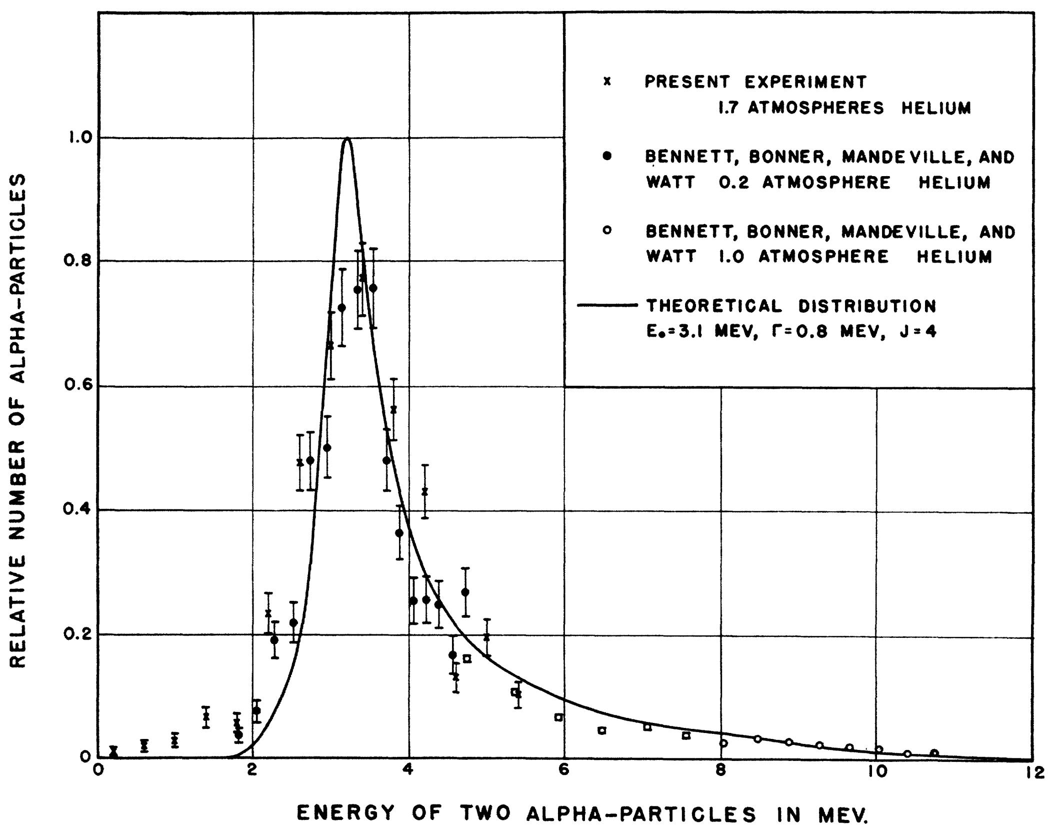


FIG. 3. The relative number of alpha-particle pairs as a function of their energy in the region of the maximum at 3.3 Mev. The statistical errors are shown by the vertical lines.

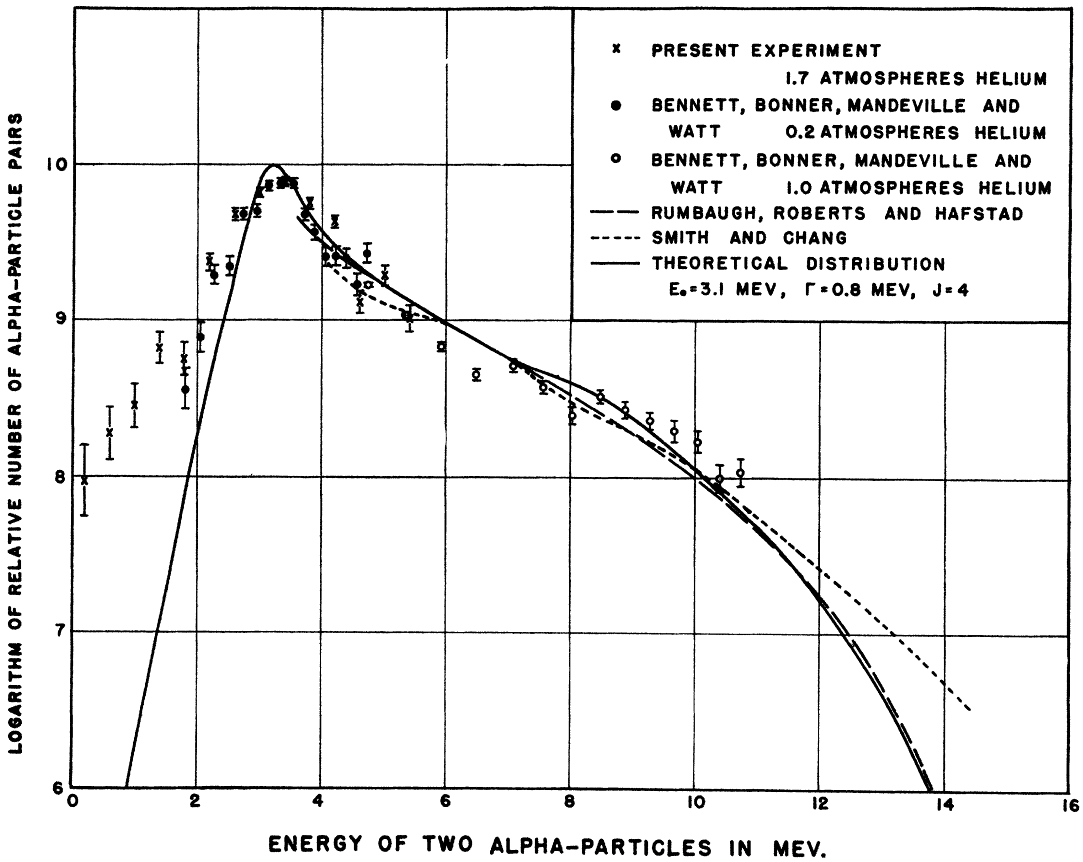


FIG. 4. The logarithm of the relative number of alpha-particle pairs as a function of their energy. Collected data of several authors are shown.

were converted to energy values and then grouped in equal energy intervals. The resulting distribution is shown by the crosses in Fig. 3. The value of the ordinates on this curve have been normalized so that the value of 1.0 corresponds to 108 tracks. The most probable energy of an alpha-particle pair is 3.3 Mev and the width at half-height is 1.2 ± 0.2 Mev. This width has been corrected for the finite energy intervals which were used. Some of the shorter tracks included in the distribution were undoubtedly neutron recoils; the control circuit, which turned off the ion source during expansion, was only used during about half of the experiment.

No evidence was found for a group of very short-range alpha-particles which would correspond to the disintegration energy of the ground state of Be^8. The combined track length of both alpha-particles, according to Wheeler's[6] estimate of the mass of Be^8, is about 5 mm. Tracks of half this length would certainly have been noticed in our experimental arrangement. Failure to observe a group of such particles is in agreement with the arguments based on selection rules that Be^8 in the ground state would not be formed in this reaction.[14,15]

The data of Bennett, Bonner, Mandeville, and Watt[12] can be compared to the present results if a suitable correction is made for the penetration of the Li^8 atoms into their target. 3.3 mm must be added to the range of each alpha-particle to make the maxima of the two curves coincide. These corrected data are shown in Fig. 3. For these data the values of the ordinates have been normalized so that the value 1.0 corresponds to 91 tracks. The width at half-height for this adjusted distribution is 1.0 ± 0.2 Mev. The two

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[15] Christy, Cohen, Fowler, Lauritsen, and Lauritsen, Phys. Rev. **72**, 698 (1947).

widths quoted above are essentially the same as that recently obtained by Christy, Cohen, Fowler, Lauritsen, and Lauritsen.[15] At higher energies the data of Rumbaugh, Roberts, and Hafstad[13] as well as those of Smith and Chang[11] are more accurate than cloud-chamber data and are included in Fig. 4. However, these results need to be corrected for the recoil of the Li^8 atoms into the target. A more or less arbitrary value of 0.2 cm was added to the range of each alpha-particle. This is a smaller adjustment than was necessary for the data of Bennett, Bonner, Mandeville, and Watt,[12] who used a higher bombarding energy.

5. DISCUSSION OF RESULTS

Attempts have been made to fit the experimental data with various theoretical distributions.[6,13] The Gamow-Teller distribution can be made to give good agreement at the higher energy values but not in the vicinity of the peak of the distribution curve. The Wheeler theory gives too few particles at the higher energies and too many particles at the very low energies. If we multiply the Wheeler distribution by the penetrability of one alpha-particle through the Coulomb barrier of the other alpha-particle, we have the following distribution:

$$N_\alpha dE_\alpha = \frac{P_{\alpha J}(Q-2E_\alpha)^5}{(E_0-2E_\alpha)^2+\frac{1}{4}\Gamma^2},$$

where $P_{\alpha J}$ is the penetrability of one alpha-particle through the Coulomb barrier of the other alpha-particle from the breakup of an excited state in Be^8 which has J units of total angular momentum. Formulae for $P_{\alpha J}$ have been given by Bethe.[16] This new distribution gives good agreement with experimental results when J is taken equal to 4, $E_0=3.1$ Mev, and $\Gamma=0.8$ Mev. The mean time of existence of such a level is about 8×10^{-22} sec. In this time an electron, traveling with essentially the velocity of light, could travel 2.4×10^{-11} cm. This is about equal to the wave-length of an electron having an energy of about 6 Mev. Hence the $^*Be^8$ breaks up before the electron is completely out of its nuclear field, and the penetrability of the alpha-particles cannot be neglected. The peak of the theoretical distribution curve is allowed to extend above the experimental points since the use of finite energy intervals in obtaining the experimental distributions flatten and widen such a peak. The experimental points at energies below the maximum lie consistently above the theoretical curve, but this is what would be expected from the inclusion of a few neutron recoils. Further experiments, free from neutron effects, are needed in this same region for comparison with theory. Figure 4 shows that the theoretical curve agrees quite well with the experimental data of Rumbaugh, Roberts, and Hafstad[13] to about 14 Mev.

Note added in proof: Agreement can also be obtained from this theoretical relation if we assume that there are two levels in Be^8 (one at 3.2 Mev with $J=2$, and a broad level at 7–9 Mev) concerned in the breakup. In this case somewhat better agreement is obtained at low energies. Theoretical calculations predict two such levels.[6]

The energy and width of this level in $^*Be^8$ is nearly the same as that found by Dee and Gilbert[17] in the reaction $B^{11}(p,\alpha)^*Be^8$. They concluded that Be^8 was excited to a 3.0-Mev level which had a width of about 1 Mev. An analysis of the same data by Bethe[18] indicated a level at 2.8 Mev with a width of 0.8 Mev.

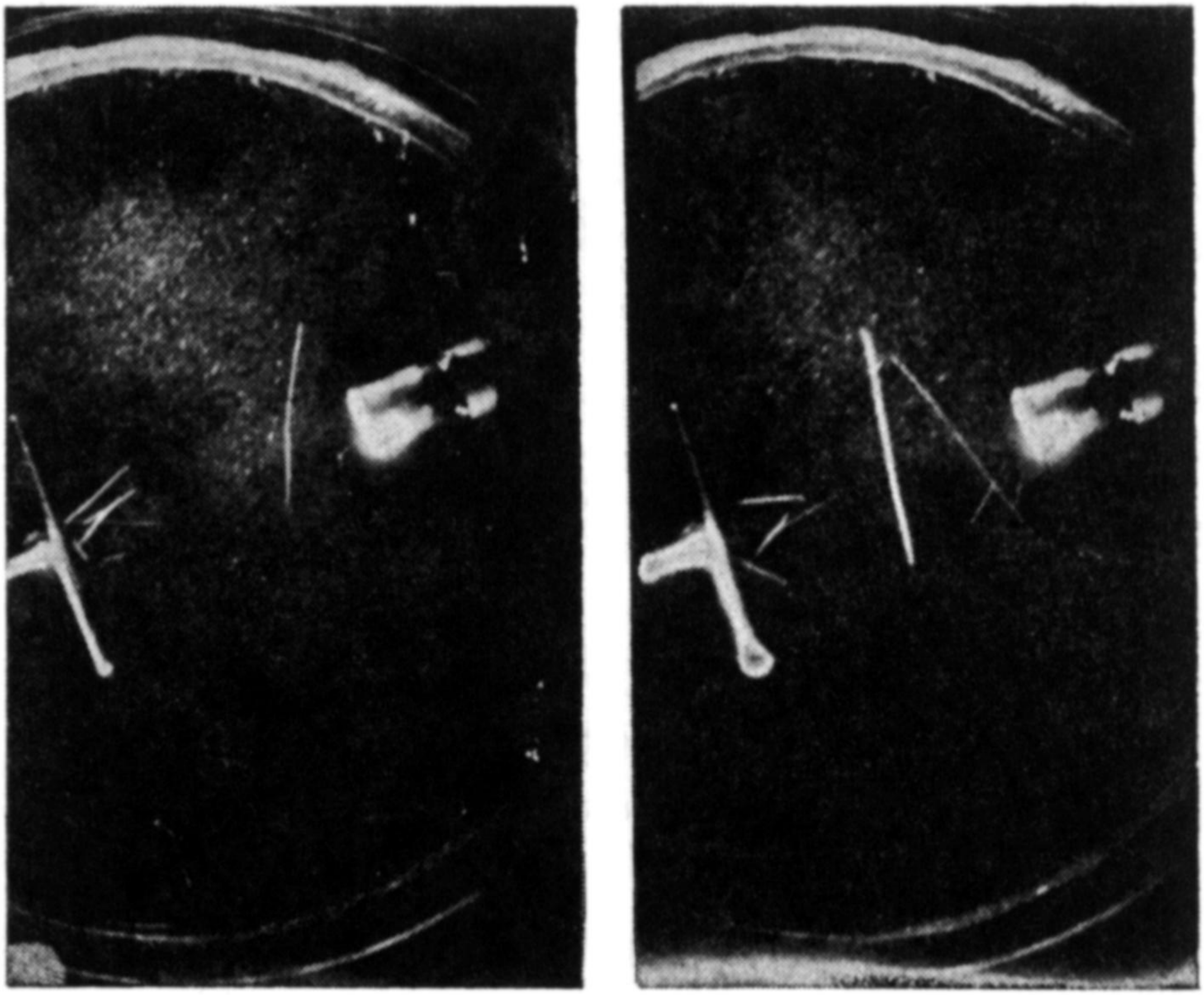
If the value of J is equal to 4 for $^*Be^8$ and if the beta-decay of Li^8 involves a transition $\Delta J=\pm 1$, it seems probable that the ground state of Li^8 has a value of $J=3$. Hence, in reaction (1) only deuterons having at least one unit of orbital angular momentum will be effective in producing Li^8.

We are indebted to the Office of Naval Research and the Research Corporation for financial support.

[16] H. A. Bethe, Rev. Mod. Phys. 9, 166, 178 (1937).

[17] Dee and Gilbert, Proc. Roy. Soc. **154**, 279 (1936).

[18] H. A. Bethe, Rev. Mod. Phys. 9, 218 (1937).



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