Disintegration of Lithium by Deuterons

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The energy distribution of the neutrons from the disintegration of lithium by 0.85 MEV deuterons has been determined by the method of recoil protons in a high pressure cloud chamber. The results of the experiment indicate that the neutrons come from the two reactions

$$_3Li^7+_1H^2\rightarrow 2_2He^4+_0n^1; \quad _3Li^7+_1H^2\rightarrow _4Be^8+_0n^1.$$

The neutrons from the first reaction (95 percent of the disintegrations) have a continuous energy distribution, while the neutrons from the second reaction (5 percent of the disintegrations) are nearly homogeneous, with a maximum energy of 13.3±0.5 MEV. From these data, the mass of $_4Be^8$ was calculated to be 0.3±0.75 MEV greater than that of two alpha-particles.

WHEN lithium is bombarded by deuterons, the following nuclear reactions are known to occur:

$$_3Li^6+_1H^2\rightarrow 2_2He^4; \quad (1)$$
$$_3Li^6+_1H^2\rightarrow _3Li^7+_1H^1; \quad (2)$$
$$_3Li^7+_1H^2\rightarrow 2_2He^4+_0n^1. \quad (3)$$

The first two of these reactions have been investigated by Lawrence,[1] Dee and Walton,[2] Oliphant, Kinsey and Rutherford,[3] and by Cockcroft and Walton.[4] The emission of neutrons when lithium is bombarded by deuterons was first reported by Crane, Lauritsen and Soltan.[5] Experiments done with the separated isotopes of $_3Li^6$ and $_3Li^7$ by Oliphant, Shire and Crowther[6] have shown that the disintegration products had been attributed to the proper isotope.[7] Oliphant, Kempton and Rutherford[8] have determined the energies of the alpha-particles liberated in reaction (3).

The purpose of the experiment described below was to investigate the energy distribution of the neutrons liberated in the disintegration of lithium by 0.85 MEV deuterons. In particular, we were interested in determining the maximum energy of the neutrons, and in investigating the probability of the transformation of $_3Li^7$ into $_4Be^8$ according to the reaction

$$_3Li^7+_1H^2\rightarrow _4Be^8+_0n^1. \quad (4)$$

There is evidence that $_4Be^8$ is formed in other disintegrations. Kirchner and Neuert[9] proposed the reaction

$$_5B^{11}+_1H^2\rightarrow _4Be^8+_2He^4$$

and Crane and Lauritsen[10] suggested that the γ-rays emitted when lithium is bombarded with protons may indicate the formation of Be^8 by capture.

We have already published, in a Letter to the Editor[11] a preliminary report of the evidence for the formation of $_4Be^8$ in the disintegration of lithium by deuterons.

EXPERIMENTAL PROCEDURE

In previous papers[12] we have described our method of determining neutron energies by observing recoil proton tracks in a high pressure cloud chamber filled with methane. We can measure a track approximately 8.8 cm long in our chamber; hence, when the chamber is operated at an expanded pressure of 14.7 atmospheres it will stop a particle which has a range of 126 cm in air. In the present experiment, we have altered our procedure due to the very long ranges (over 190 cm in air) of the recoil protons projected by neutrons released in the disintegration of lithium. We placed a sheet of mica of 114 cm air equivalent across the center of the chamber in a plane perpendicular to a line drawn to the target. With this apparatus a series of runs were made in which we were able to investigate the range interval of approximately 125 cm to 240 cm, or the energy interval of 10.5 MEV

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* National Research Fellow.

[1] Lawrence, Phys. Rev. **44**, 55 (1933).

[2] Dee and Walton, Proc. Roy. Soc. **A141**, 733 (1933).

[3] Oliphant, Kinsey and Rutherford, Proc. Roy. Soc. **A141**, 722 (1933).

[4] Cockcroft and Walton, Proc. Roy. Soc. **A144**, 704 (1934).

[5] Crane, Lauritsen and Soltan, Phys. Rev. **44**, 692 (1933).

[6] Oliphant, Shire and Crowther, Nature **133**, 377 (1934).

[7] We might also expect to observe neutrons from the reaction $_3Li^6+_1H^2\rightarrow _2He^4+_2He^3+_0n^1$ which appears to be exothermic by 1.3 MEV, but apparently this mode of disintegration is quite improbable.

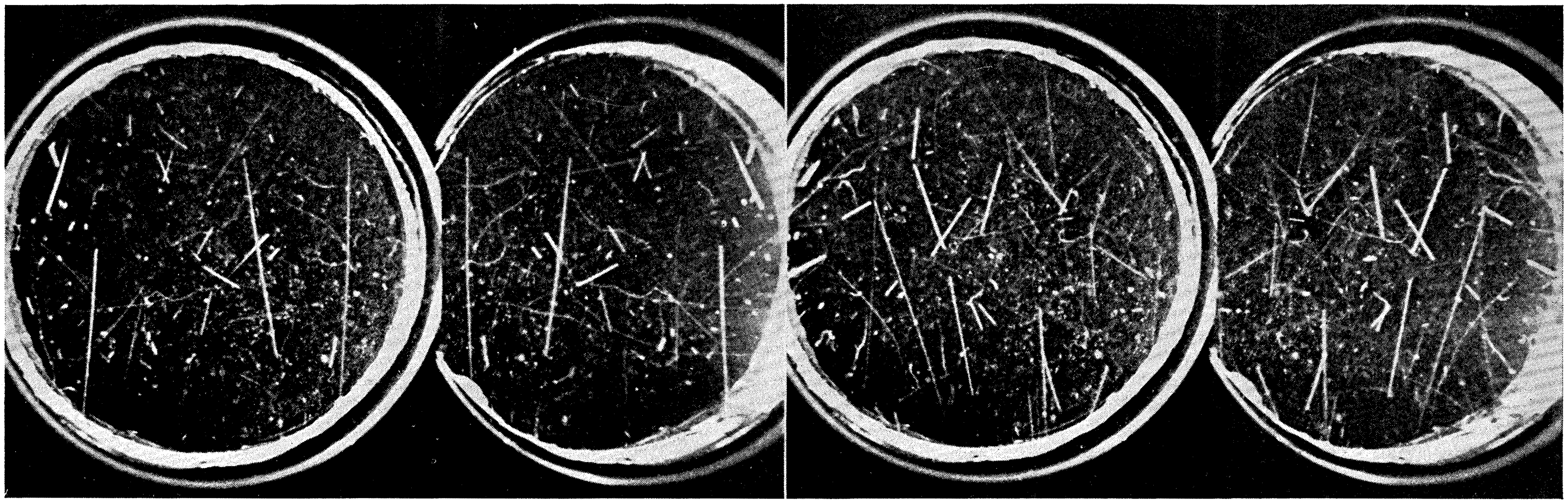
[8] Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **A149**, 406 (1935).

[9] Kirchner and Neuert, Physik. Zeits. **35**, 293 (1934).

[10] Crane and Lauritsen, Phys. Rev. **47**, 420 (1935).

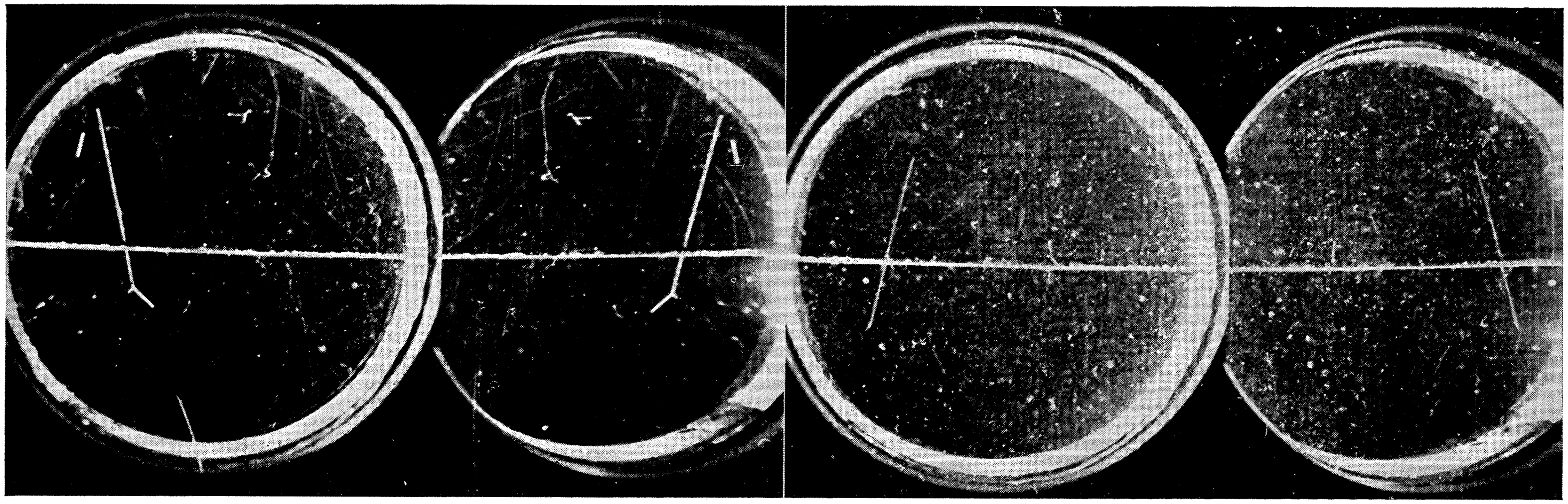
[11] Bonner and Brubaker, Phys. Rev. **47**, 973 (1935).

[12] Brubaker and Bonner, Rev. Sci. Inst. **6**, 143, (1935); Phys. Rev. **47**, 910 (1935).



1*A* 1*B*

FIG. 1. Recoil protons in the cloud chamber when operated at 14.7 atmospheres pressure.



2*A* 2*B*

FIG. 2. Photographs of recoil protons which penetrate the mica sheet in the center of the chamber. On *A* there is a proton of range 123 cm, which made a collision with a proton near the end of its range. The recoil proton in *B* which goes through the mica had a range of 168 cm.

to 15.3 MEV. With a sheet of mica of 58 cm air equivalent, we investigated the energy interval of 8.4 MEV to 11.2 MEV, and with no mica in the chamber we covered the interval 2.2 to 8.4 MEV. Because the tracks of the lower energy protons were too short to be observed at a pressure of 14.7 atmospheres, two more series of runs were made. In one of these we used methane at a pressure of 2.67 atmospheres, and in the other we used hydrogen at a pressure of $\frac{1}{2}$ atmosphere.

We measured only those proton tracks which made angles less than 8° with a line drawn to the center of the source. A proton projected at an angle of 8° by a neutron gets 98.1 percent of its energy, so recoil protons which are projected at angles less than 8° have essentially the same energy as the incident neutrons. Our previous work on the neutrons from beryllium[12] has shown that the number of tracks caused by scattered neutrons which appear to be in this angular interval is very small.

The ranges of the recoil protons were computed from the track lengths and the calculated stopping power of the gas and the mica sheet.[13] These proton ranges were then converted into proton energies by the range-velocity curve of Mano.[14] A correction has been applied to the data of each run to compensate for the unequal probabilities of observing tracks of different lengths in the chamber. This was particularly important when the mica sheet was used.

The effect of the small amount of proton contamination in the deuteron ion beam was examined by making a control run in which the bombarding ions were protons. There were less than 1/200 as many recoil protons photographed as when deuterons were used, which indicates that the proton impurity could not have been responsible for more than 1/2000 of the observed neutrons. In test runs which were made when the lithium chloride target was replaced by a brass one, less than 1/200 as many recoil protons were photographed. The few tracks which were observed were probably due to the reaction

$$_1H^2+_1H^2\rightarrow _2He^3+_0n^1.$$

However, in the present experiment the number of neutrons obtained from the bombardment of the absorbed deuterium on the target is so small that it is unimportant.

RESULTS

We have taken a total of 19,600 sets of stereoscopic photographs on which there were approximately 60,000 recoil protons. Examples of such photographs of the recoil protons are given in Figs. 1 and 2. From these photographs we have measured the ranges of 1550 recoil protons which were projected in nearly the forward direction (0°–8°). The energy distribution of these recoil protons is given in Fig. 3. The curve includes data from five overlapping series of runs which were fitted together as shown. In the lower energy portion of the curve, the number of tracks in a given 0.4 MEV interval was only about half of the number indicated.

The upper curve of Fig. 3 gives the distribution of recoil protons but not necessarily the distribution of the primary neutrons. A variation in the neutron-proton collision area with energy would make the neutron distribution curve differ from the proton curve.[15] It is well known that the collision area increases as the energy of the neutrons decreases. In order to obtain the neutron distribution curve, we have taken into account the experimental variation of collision area with neutron energy as found by Bonner[16] and Dunning.[17] The collision areas[18] used were: $E\approx 0$, $\sigma=31\times 10^{-24}$; $E=1.2$ MEV, $\sigma=5.8\times 10^{-24}$; $E=2.1$ MEV, $\sigma=3.2\times 10^{-24}$; $E=5$ MEV, $\sigma=1.68\times 10^{-24}$. Thus we get the dotted curve of Fig. 2, which we believe to be the approximate form of the neutron distribution curve. It exhibits a broad maximum near 2.1 MEV; this indicates that the most probable energy of the

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[13] The gas in the chamber was 85.1 percent CH_4, 13.5 percent C_2H_6, and 1.4 percent N_2. The corresponding stopping powers were 0.86 for methane, 1.52 for ethane, and 0.99 for nitrogen. The stopping power of the mica was computed in the usual manner, using the value 1.43 mg sq. cm equivalent to one cm air.

[14] G. Mano, J. de phys. et rad. **5**, 628 (1934).

[15] Any change with energy in the angular distribution of neutron-proton collisions would also alter the neutron distribution curve from the one shown.

[16] T. W. Bonner, Phys. Rev. **45**, 601 (1934).

[17] J. R. Dunning, Phys. Rev. **45**, 586 (1934); Dunning, Pegram, Fink and Mitchell, Phys. Rev. **47**, 970 (1935).

[18] Because of differing geometrical conditions the absolute values of the target areas obtained by Bonner and Dunning were not the same, so all of Bonner's data have been multiplied by the factor 2.3 to give the same cross section as Dunning for 5 MEV neutrons.

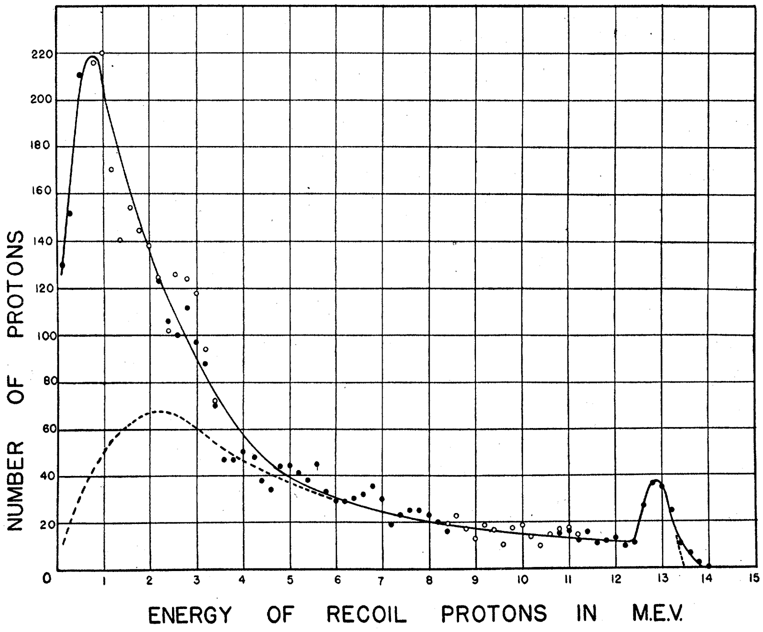

FIG. 3. The energy distribution of the recoil-protons (upper curve) primary neutrons (dotted curve).

neutrons released in the disintegration of lithium by deuterons is approximately 2.1 MEV. The mean energy under the neutron curve is 3.9 MEV.

It is possible to correlate this mean neutron energy with the mean energy of the alpha-particles which are produced in the same disintegration. Oliphant, Kempton and Rutherford[8] obtained the distribution-in-range of the alpha-particles with a differential counter, which counts the number of particles in the range interval between x and $x+\Delta x$. The corresponding energy interval, ΔE, is not a constant but is a function of x. Hence, when their data are transformed to equal energy intervals and plotted, it appears as in the curve of Fig. 4, which exhibits a maximum near 6.8 MEV. The mean energy under this curve is approximately 5.0 MEV. If we rather arbitrarily add 0.2 MEV to this value to compensate for the depth of the counting chamber, we have 5.2 MEV as the mean alpha-particle energy, in which case the mean energy of the two alpha-particles is 10.4 MEV. When this is added to the mean neutron energy of 3.9 MEV, we get 14.3 MEV for the kinetic energy appearing after the disintegration. These results were taken from two different experiments; in one of these the bombarding energy was 0.2 MEV and in the other it was 0.85 MEV. While we are uncertain as to how much of the bombarding energy appears in the respective disintegration products, we have estimated that 0.3 MEV should be subtracted if we wish to represent the case of zero bombarding energy in both cases. This calculation gives 14.0 MEV as the energy released in the disintegration. Considering the uncertainties in the mean energies of the disintegration particles, this result checks as well as could be expected with the value of 14.6±0.25 MEV found by Oliphant, Kempton and Rutherford.[8]

MASS OF $_4Be^8$

The recoil proton distribution curve, Fig. 3, shows a pronounced hump near 13 MEV, which

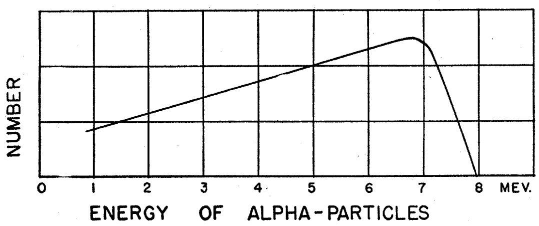

FIG. 4. The energy distribution of the alpha-particles (data of Oliphant, Kempton and Rutherford for oscillograph kicks greater than 1 cm, replotted in equal energy intervals).

we have interpreted as being due to the transformation of ${}_3\mathrm{Li}^7$ into ${}_4\mathrm{Be}^8$ and a neutron, as postulated in reaction (4). The area under the hump is approximately 5 percent of the area under the entire curve; this indicates that ${}_4\mathrm{Be}^8$ is formed in 5 percent of the disintegrations.

As the neutrons were observed at right angles to the incident deuterons, the energy of disintegration, Q, is given by

$$Q=9/8E_N-3/4E_H,$$

where E_N is the neutron energy and E_H is the energy of the incident deuteron. The extrapolated maximum neutron energy is 13.4±0.5 MEV. Because Mano's range-velocity curve is for mean and not extrapolated range, we have subtracted 0.1 MEV from our extrapolated energy. Using a neutron energy of 13.3 MEV and a bombarding energy of 0.85 MEV, we find that $Q=14.3\pm0.5$ MEV. From the value of 14.6±0.25 MEV found by Oliphant, Kempton and Rutherford for the energy of disintegration into two alpha-particles and a neutron, we calculate the mass of ${}_4\mathrm{Be}^8$ to be 0.3±0.75 MEV greater than that of two alpha-particles. A recalculation of Kirchner's mass of ${}_4\mathrm{Be}^8$ with Bethe's new isotopic scale[19] gives a mass just equal to that of two alpha-particles. Recently, Oliphant, Kempton and Rutherford[20] have shown that ${}_4\mathrm{Be}^8$ is formed according to the reactions ${}_4\mathrm{Be}^9+{}_1\mathrm{H}^1\rightarrow{}_4\mathrm{Be}^8+{}_1\mathrm{H}^2$; ${}_4\mathrm{Be}^9+{}_1\mathrm{H}^2\rightarrow{}_4\mathrm{Be}^8+{}_1\mathrm{H}^3$ and find a mass of ${}_4\mathrm{Be}^8$ which is 0.2 MEV greater than that of two alpha-particles. The present evidence seems strongly to indicate the existence of a ${}_4\mathrm{Be}^8$ nucleus with a mass slightly greater than that of two alpha-particles, although a mass equal to or less than that of two alpha-particles cannot be excluded at the present time.

We wish to thank Professor C. C. Lauritsen for valuable suggestions made during the progress of this work, and the Seeley W. Mudd Fund for its financial support.

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[19] H. A. Bethe, Phys. Rev. **47**, 633 (1935).

[20] Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **A150**, 241 (1935).

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On the Nuclear Moments of Lithium, Potassium, and Sodium[1]

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The atomic beam method of "zero moments" was applied to the measurement of the nuclear spin and hfs separation of the normal $^2S_{1/2}$ state of Li^7. The experimental arrangement was such that the precision obtained was about 1 percent. It was verified that the nuclear spin was 3/2, and the hfs separation was measured to be 0.0268±0.0003 cm^{-1}. By using the modified Goudsmit formula the nuclear magnetic moment was calculated to be 3.20 nuclear magnetons compared with the value of 3.28 calculated from hyperfine structure measurements on the $^3P_0-{}^3S_1$ group (λ5485) of $(\mathrm{Li}^7)^+$ by Breit and Doerman using wave functions. The same method applied to potassium and sodium yielded hfs separations of 0.0154±0.0002 and 0.0596±0.0006 cm^{-1}, respectively, which lead to nuclear magnetic moments of 0.397 and 2.08 nuclear magnetons. With another arrangement of the apparatus yielding higher resolution than was previously obtained it was possible to set the value of 5/2 as an upper limit for the spin of the K^{41} nucleus. With the same arrangement applied to lithium it was found that the nuclear spin of Li^6 is 2/2 or greater and that the magnetic moment of the nucleus is of the order of magnitude of that of the deuteron.

INTRODUCTION

THE hyperfine structure of the $(\mathrm{Li}^7)^+$ spectrum and the band spectra of the $\mathrm{Li}_2{}^7$ molecule have been studied by a number of investigators.[2] The band spectra results have yielded a value of $3/2\ h/2\pi$ for the nuclear spin of Li^7, which is consistent with the results

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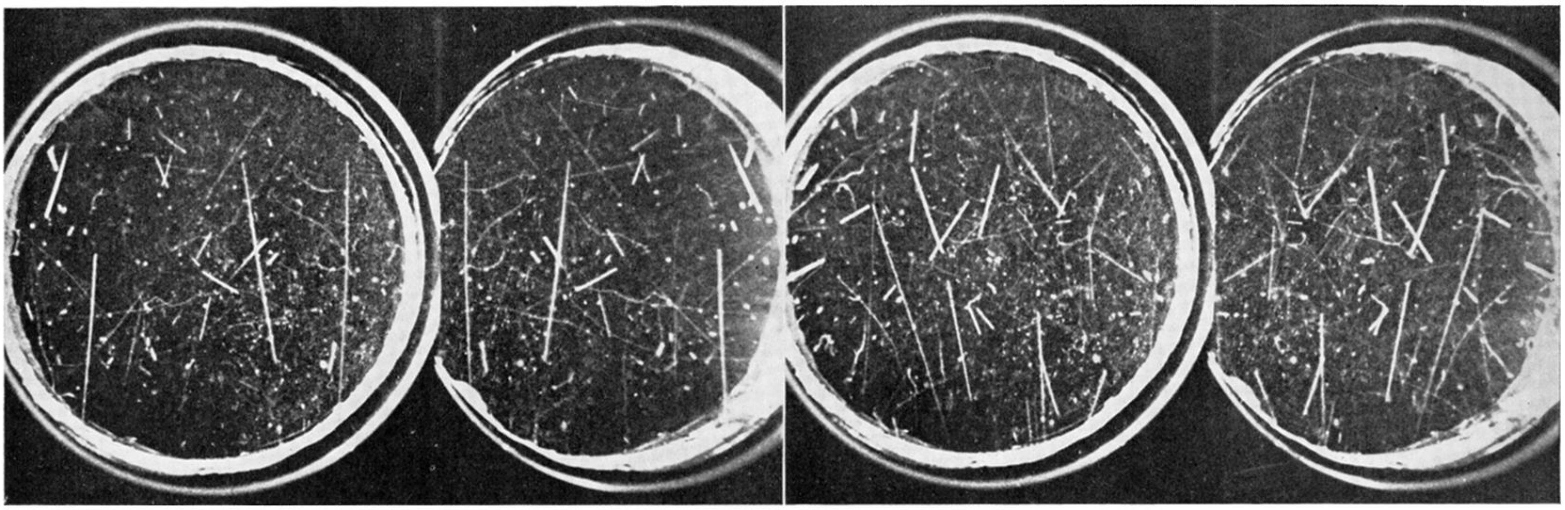
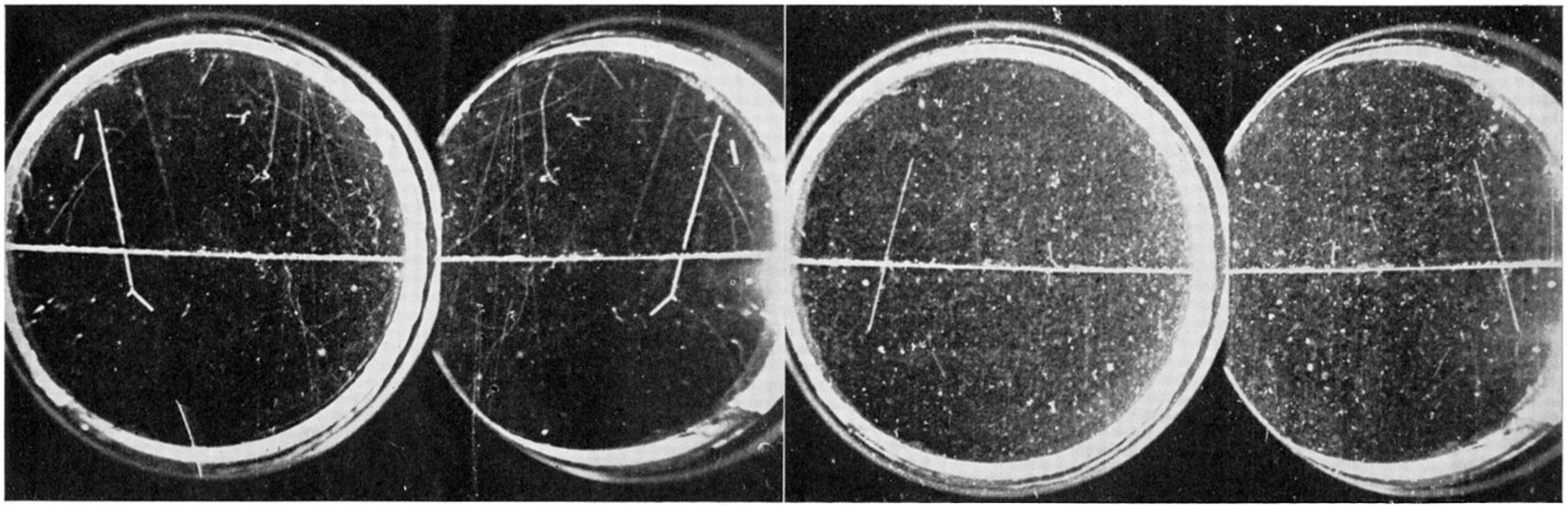
[1] A preliminary report on the spin and magnetic moment of Li^7 was given at the Washington meeting of the Am. Phys. Soc. Fox, Millman and Rabi, Phys. Rev. **47**, 801 (1935).

[2] Schüler, Zeits. f. Physik **66**, 431 (1930); Harvey and Jenkins, Phys. Rev. **35**, 789 (1930); Güttinger and Pauli, Zeits. f. Physik **67**, 743 (1931); Goudsmit and Inglis, Phys. Rev. **37**, 328 (1931); Granath, Phys. Rev. **42**, 44 (1932); Ladenburg and Levy, Zeits. f. Physik **88**, 449 (1934).



1*A* 1*B*

FIG. 1. Recoil protons in the cloud chamber when operated at 14.7 atmospheres pressure.



2*A*　　2*B*

Fig. 2. Photographs of recoil protons which penetrate the mica sheet in the center of the chamber. On *A* there is a proton of range 123 cm, which made a collision with a proton near the end of its range. The recoil proton in *B* which goes through the mica had a range of 168 cm.