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The Beta-Ray Spectra of Li^8 and B^{12}

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Cloud chamber measurements have been made on the beta-ray spectra of Li^8 and B^{12}. The use of strict criteria in the selection of tracks for measurement is thought to have reduced preference for tracks at one or the other end of the spectrum. Separate measurements near the upper limits give for both spectra upper limits by inspection of 12.0 ± 0.6 Mev. Evidence is presented that the protons emitted during the formation of Li^8 have nearly zero energy. It is thus possible to determine the energy available in the radioactive disintegration of Li^8 into an electron, neutrino and two alpha-particles. Comparisons are made between the experimental Li^8 spectrum and those predicted by using the K-U and Fermi theories in conjunction with the recently measured alpha-particle distributions. It is shown that the K-U theory demands a reaction energy 5 Mev greater than that which is available. An indication is given that the protons emitted during the formation of B^{12} have an energy of at least 1 Mev, while a proton energy of nearly zero is required if the K-U upper limit, 14.5 Mev, is correct.

Introduction

The cloud chamber method of measuring beta-ray spectra is most effective when applied to such high energy spectra as those of Li^8 and B^{12}. Distortion of the spectra due to scattering of the electrons in the gas is entirely negligible over the greater part of the energy range. The short lifetimes of Li^8 and B^{12} give no inconvenience, as they would in a spectrograph, because the target can be bombarded immediately before each expansion.

Accurate measurements of the high energy spectra lead to results of considerable theoretical importance: The mass differences in such isobaric pairs as Li^8-Be^8 and $B^{12}-C^{12}$ give promise of being important in the determination of the energy level schemes of light nuclei. The recent observation by Lewis, Burcham and Chang[1] of a continuous alpha-particle emission associated with the disintegration of Li^8 indicates that the beta-ray spectrum of this isotope is complex. It is therefore of interest to compare this spectrum with that of B^{12}, which is presumably not complicated by subsequent splitting into alpha-particles. A further point of interest is that the energy balances in the Li^8 and B^{12} disintegrations furnish by far the most clear proof that the energy lost by a nucleus during a beta-disintegration is that corresponding to the upper limit of the spectrum. It is also possible, by means of the energy balances, to discover whether or not the K-U upper limit demands more energy than is available in the reaction.

The beta-rays from Li^8 and B^{12} were first observed and measured by Crane, Delsasso, Fowler and Lauritsen,[2] by the cloud chamber method. The present experiment is an attempt to measure with greater accuracy the shapes and upper energy limits of these spectra. The principal improvements in the method used lie in the strict criteria used in selecting the tracks for measurement, and in the fact that overlapping measurements were made at several magnetic field strengths. In this way it is believed that the preference for tracks at one or the other end of the spectrum has been reduced.

Experimental Method

The cloud chamber used in the work described is 15 cm in diameter and 3 cm deep, filled with air and ethyl alcohol vapor at atmospheric pressure. It is equipped with a pair of air core coils which produce a magnetic field for bending the tracks in the plane of the chamber. Calibration of the field strength was made by means of a pick-up coil and standard mutual inductance. The measurement was made automatically at the time of expansion of the cloud chamber, in order to eliminate any question as to the building up of the field, and is considered accurate to within 2 percent. The error introduced by the nonuniformity of the field over the area of the chamber is less than 1 percent. A vernier resistance in the field circuit of the generator supplying the current to the coils made it

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

[2] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **47**, 971 and 887 (1935).

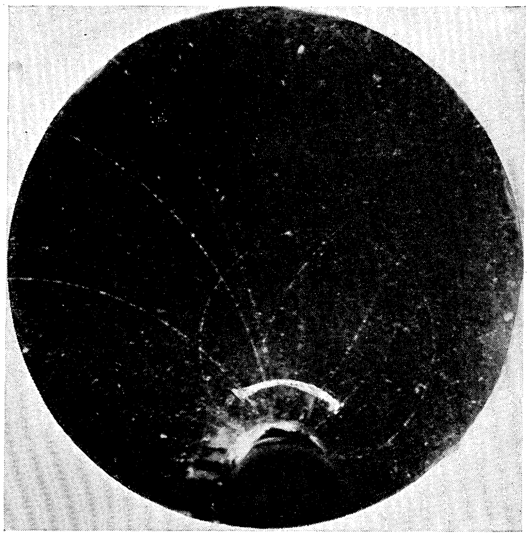


FIG. 1. Li^8 beta-rays from a thin walled thimble inside the cloud chamber. Three of these tracks satisfy the requirements for measurement.

possible to keep the field strength constant to within 1 percent at all times.

Li^8 and B^{12} were produced by bombarding targets of lithium metal and amorphous boron with deuterons of about 500 kv energy, accelerated by a high potential transformer-vacuum tube apparatus.[3] For measurements of the shapes of the beta-ray spectra the target was placed in a thin walled (0.2 mm) aluminum thimble, which projected into the cloud chamber through the glass top plate. The targets were sloped toward the center of the chamber, so that the only material which the beta-rays passed through was the 0.2 mm aluminum wall. The tracks were illuminated by means of a carbon arc, flashed at 300 amperes, and were photographed with a Sept camera mounted directly above the chamber. An example of the photographs obtained is shown in Fig. 1 and indicates the position of the target in the cloud chamber. A motor driven contact system was used to operate the tube and cloud chamber in the proper sequence. For lithium (0.9 second half-life) the expansion occurred about two seconds after bombardment, and for boron (0.02 second half-life) the expansion was delayed only 1/25 second. The length of time of bombardment was 1 second for lithium and 0.1 second for boron.

In order to obtain additional data at the upper limits of the spectra, an arrangement was used in which the target was placed outside the cloud chamber and coils, and the particles were allowed to pass into the chamber through a thin window. The path of the particles in the magnetic field outside the chamber was such that only those of radius of curvature greater than 6 cm were able to reach the window. All other particles were stopped by suitably placed absorbing blocks or were bent away by the magnetic field. A graphical estimate showed that for particles with radius of curvature greater than 8 cm (7 Mev) the variation with curvature of the solid angle subtended at the target by the chamber window was not appreciable. It was not possible for particles scattered from the faces of the field coils to enter the chamber and still remain closely enough in the horizontal plane to satisfy the criteria for measurement. The picture shown in Fig. 2 was obtained with this arrangement.

The curvatures of the tracks were measured by matching their full size projected images with circles drawn on a card. The size of the projected image was adjusted by means of a photograph of a meter stick placed in the chamber at the position in which the tracks were formed. This method of adjustment is accurate to about 1 percent. To eliminate a curvature

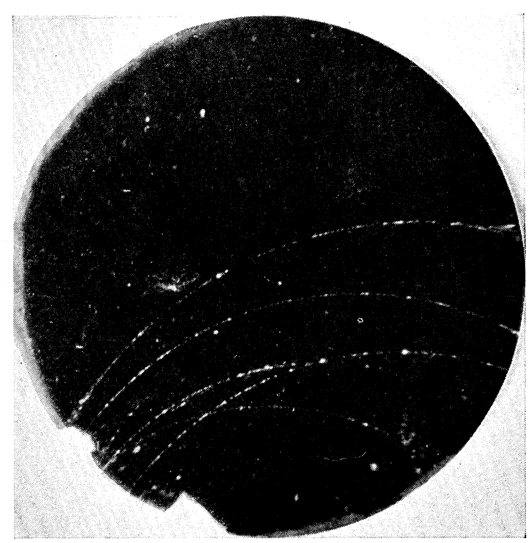


FIG. 2. Li^8 beta-rays entering the cloud chamber through a thin window. This is the arrangement used for measuring the upper limits of the Li^8 and B^{12} spectra.

[3] Crane, Phys. Rev. 52, 11 (1937).

dependent preference in the selection of tracks for measurement the following criteria were set up:

(1) In order to make sure that all selected tracks could travel 10 cm without striking the chamber wall, it was required that they emerge from the source within the region marked by the white line in Fig. 1.
(2) The measurable portion of each track selected was required to be at least 10 cm long.

It is seen that three of the tracks in Fig. 1 satisfy these requirements. The criteria used insure that the effective solid angle subtended at the source by the active part of the cloud chamber is independent of the curvature of the tracks. This is a frequent source of distortion in cloud chamber measurements where the only requirement for the selection of tracks is measurability.

Results

In measuring the shapes of the spectra, three different values of the magnetic field were used for lithium, and two for boron. The data obtained with the various fields were adjusted to the same scale by making the areas under the overlapping portions equal. The curves are shown in Figs. 3 and 4. The fact that the overlapping portions of the curves have about the same shape is some indication that there is no great preference for the selection of tracks of either high or low curvature. The results of the measurements on the upper limits of the spectra, made with the target outside the chamber, are shown in Fig. 5. The values obtained for the upper limits by inspection are 12 Mev for both lithium and boron, and are considered accurate to within 5 percent, as far as the errors in the actual measurements are concerned. K-U and Fermi plots are given for boron (Fig. 6) but are not given for lithium because it is not a simple spectrum.

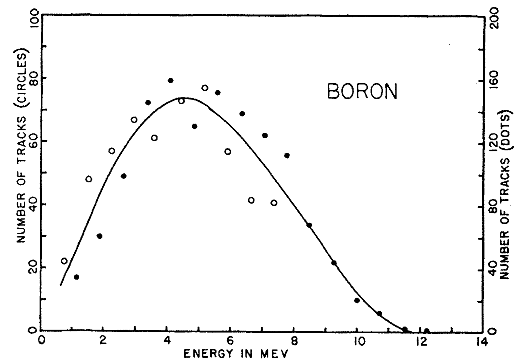


FIG. 4. Experimental spectrum of beta-rays from B^{12}. Circles are for 1220 gauss field (right-hand ordinate scale). Dots are for 2440 gauss field (left-hand ordinate scale).

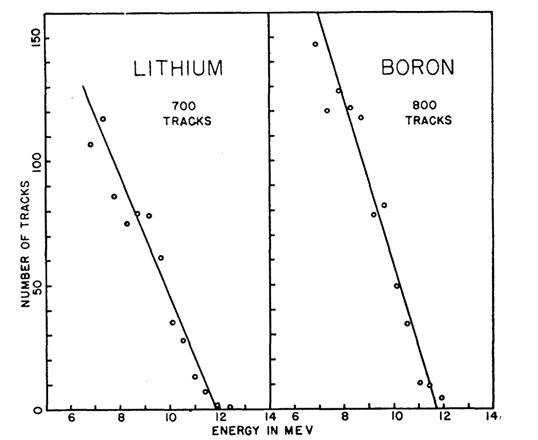


FIG. 5. Plots of separate data obtained near the upper limits of the Li^8 and B^{12} spectra.

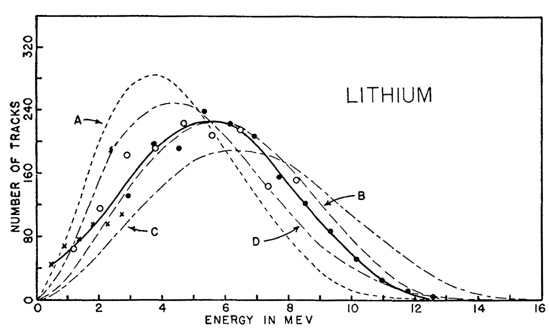


FIG. 3. Heavy curve: experimental spectrum of Li^8. Crosses are for 780 gauss field, circles are for 1490 gauss, dots are for 2670 gauss. The same ordinate scale applies to all points. Curve A: K-U theory with F-L alpha-particle distribution. Curve B: Fermi theory with F-L alpha-particle distribution. Curve C: Fermi theory with R-R-H alpha-particle distribution. Curve D: K-U theory with R-R-H alpha-particle distribution.

With the use of the boron target, a number of photographs were taken of expansions made during bombardment, and with a low magnetic field strength. One of these is reproduced in Fig. 7. The total thickness of the aluminum windows between the target and cloud chamber was such that only the 90 cm group of protons from $B^{10}+H^2$ were able to enter the chamber. It was found that the electrons greatly outnumbered the protons of this range group. Our observations gave no reason for modifying the ratio of 20 to 1 given by Crane, Delsasso, Fowler and Lauritsen.[2]

Discussion

Lithium

The reaction describing the formation of Li^8 by deuteron bombardment is probably

$$Li^7+H^2 \rightarrow Li^8+H^1+Q_1. \tag{1}$$

Q_1 has never been measured directly, but evidence that it is nearly zero can be obtained by comparing the excitation curve for reaction (1) with that of the alternative reaction

$$Li^7+H^2 \rightarrow 2He^4+n^1+Q_2, \tag{2}$$

which is responsible for most of the neutrons from Li^7+H^2. The reaction probability for (1) is, to a first approximation, proportional to P_DP_P/E, where P_D and P_P are the potential barrier penetrabilities of the incident deuteron and the escaping proton, and E is the bombarding voltage. Since the neutron is uncharged, the corresponding reaction probability for (2) is proportional to P_D/E. For the bombarding voltages E_1 and E_2 at which the two reactions just become observable, the reaction probabilities should be about equal. On the assumption that

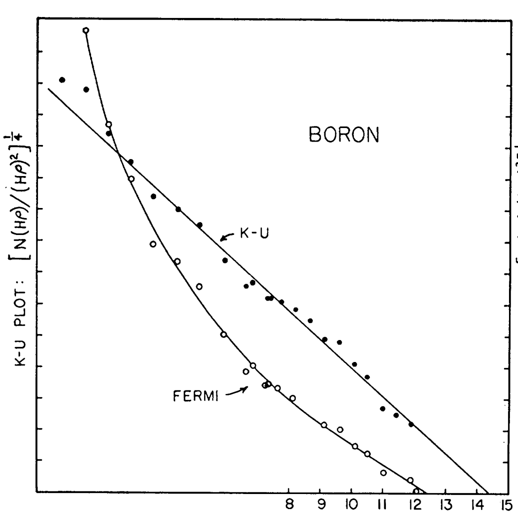


FIG. 6. K-U and Fermi plots for B^{12}. These include the separate upper limit data shown in Fig. 5.

the internal reaction probabilities are of the same order of magnitude, we can write

$$\frac{P_D(E_1)P_P(E_p)}{E_1} \backsimeq \frac{P_D(E_2)}{E_2}, \tag{3}$$

where E_p is the energy of the escaping proton in reaction (1). According to the excitation curves obtained by Rumbaugh and Hafstad,[4] $E_1 \sim 400$ kv and $E_2 \sim 200$ kv. Eq. (3) can now be solved for E_p by using the expressions for the barrier penetrabilities given by Bethe.[5] The result is $E_p \sim 200$ kv. Hence $Q_1 \sim 0$.

Another indication that Q_1 is of this order of magnitude has been given by Rumbaugh, Roberts and Hafstad,[6] as a result of experiments on the separated isotope Li^7. They found no protons emitted with range greater than 1.7 cm when Li^7 was bombarded with deuterons at 860 kv. This sets an upper limit for Q_1 of 260 kv. A lower limit, $Q_1=-300$ kv, is set by the fact that reaction (1) occurs at all at 400 kv bombarding voltage.

The radioactive decay of Li^8 is probably described by

$$Li^8 \rightarrow 2He^4+e^-+\nu+2Q_\alpha+W_0. \tag{4}$$

The total energy released in (4) is 15.8 ± 0.5 Mev. This is determined by using 0 ± 0.3 Mev for Q_1, and the mass scale of Livingston and Bethe.[7] It has been found by Rumbaugh, Roberts and Hafstad,[6] and also by ourselves that no gamma-rays are emitted in reaction (4). We can therefore write

$$W_0+2Q_\alpha=15.8 \pm 0.5 \text{ Mev}, \tag{5}$$

on the assumption that the energy lost by the nucleus in the beta-process is equal to the upper limit of the beta-ray spectrum, W_0.

In order to determine the expected shape of the beta-ray spectrum on the basis of the K-U or the Fermi theory, we must treat the spectrum as a superposition of an infinite number of simple spectra, and may represent it by

$$\int_0^{15.8} A(W_0)F(W, W_0)dW_0, \tag{6}$$

[4] Rumbaugh and Hafstad, Phys. Rev. **50**, 681 (1936).
[5] Bethe, Rev. Mod. Phys. **9**, 69 (1937).
[6] Rumbaugh, Roberts and Hafstad, Phys. Rev. **51**, 1106 (1937).
[7] Livingston and Bethe, Rev. Mod. Phys. **9**, 245 (1937).

in which $F(W, W_0)$ is a simple spectrum with upper limit W_0 and in which $A(W_0)$ is its weight factor given by

$$A(W_0)\int_0^{W_0} F(W, W_0)dW = N_\alpha, \qquad (7)$$

where N_α is the number of alpha-particles of energy $\frac{1}{2}(15.8 - W_0)$.

In Fig. 3 we compare our experimental lithium spectrum (heavy curve) with that predicted by Eq. (6). Curves A and B are obtained by using for $F(W, W_0)$ the K-U and the Fermi distributions, respectively, together with the continuous alpha-particle distribution given by Fowler and Lauritsen.[8] The calculated curves are adjusted to the same area as the experimental curve. The calculation of curve A from the K-U theory involves only the conservation Eq. (5), and is not fitted except for the adjustment of the ordinate scale. The usual method of fitting K-U curves to experimental spectra is to make the maxima and center portions of the curves coincide. This method leads to the prediction of a theoretical upper limit. In order to make the maximum in curve A coincide with that of the experimental curve we would have to use a reaction energy more than 5 Mev greater than that which is known to be available.

FIG. 7. Protons of the 90 cm range group and electrons from a target of $B^{10}+B^{11}$ bombarded with deuterons.

The true upper limit of the Li^8 spectrum must be the difference between the total energy, 15.8 Mev, and twice the minimum alpha-particle energy. Although the alpha-particle intensity may become exceedingly small near zero energy, it is reasonable, from a theoretical standpoint, to expect it to reach to zero energy; therefore the true upper limit is probably 15.8 Mev. Fowler and Lauritsen's curve tends to indicate that there are relatively few alpha-particles below 0.8 Mev, and our beta-ray spectrum supports this by giving a fairly definite cut-off at about 12 Mev. However, if enough data were obtained (7000 photographs were used in the present lithium spectrum) the experimental spectrum should eventually extend to 15.8 Mev.

Rumbaugh, Roberts and Hafstad[6] have found an alpha-particle distribution which seems to show no tendency to decrease at an energy as low as 0.9 Mev, whereas the Fowler and Lauritsen distribution decreases below 1.3 Mev. Taking an extreme case, namely assuming that the alpha-particle distribution has a maximum at zero energy, we have derived the curves C and D, Fig. 3, from the Fermi and K-U formulae, respectively.

The maximum in the neighborhood of 1 Mev which probably exists in the alpha-particle distribution can be made understandable by postulating a virtual level for the system of two alpha-particles (Be^8) at an energy of 2 or 3 Mev. This would be a very short lived state and would therefore have a great breadth in energy. One cannot be sure, however, that the maximum owes its position to a level of that energy in Be^8. Let us assume (1) that the intensity of alpha-particles decreases at low (alpha) energy because of the potential barrier for the separation of the pair of alpha-particles, and (2) that the intensity of beta-rays falls off at low (beta) energy according to the Sargent relation. The product of the Sargent and Gamow probabilities would predict an alpha-particle distribution of about the shape observed by Fowler and Lauritsen, but with a maximum at an energy corresponding to half the height of the mutual barrier for two alpha-particles. Using Bethe's value for the alpha-particle radius, the maximum is found to

[8] Fowler and Lauritsen, Phys. Rev. **51**, 1102 (1937).

be at 0.9 Mev. This is somewhat below that found by Fowler and Lauritsen, but is consistent with the distribution of Rumbaugh, Roberts and Hafstad.

Boron

The reactions involved in the case of boron are probably

$$B^{11}+H^2 \rightarrow B^{12}+H^1+Q_3; \tag{8}$$

$$B^{12} \rightarrow C^{12}+e^-+\nu+Q_4. \tag{9}$$

We have been able to observe no gamma-ray emission during the radioactive decay. Q_4 should therefore be the energy of the upper limit of the beta-ray spectrum, given by

$$Q_4 = 14.5 \pm 0.2 \text{ Mev} - Q_3.$$

The protons emitted from boron bombarded with deuterons have only been investigated when both isotopes are present, and the emission of several range groups of protons from B^{10} have made it difficult to identify the slow proton group which should accompany the formation of B^{12}. Q_3 is therefore not known from direct experiment.

By counting the number of beta-ray tracks in the cloud chamber as a function of the bombarding voltage, we have obtained the excitation curves for the reactions producing Li^8 and B^{12}. These are shown in Fig. 8. The voltage scale was calibrated by means of the resonance[9] for the $F+H^1$ gamma-rays at 328 kv. It appears that the boron reaction begins at a voltage as low as 250 kv, while the lithium reaction, as already found by other observers,[4] sets in at about 400 kv. This may be interpreted as indicating that the emitted proton in the boron reaction has sufficient energy to escape easily through the potential barrier, which is effectively about 1.4 Mev high. That is, the proton probably has an energy of at least 1 Mev. The upper limit of the beta-ray spectrum given by the K-U plot (Fig. 6) is 14.5 Mev, which leaves about zero energy for the escaping proton at 250 kv bombarding voltage. Although the errors in such a calculation may easily be 0.5 Mev, this is slight evidence that the upper limit given by the K-U plot is too high. On the other hand, the fact that the boron reaction sets in at about 150 kv lower voltage than does the lithium reaction could be accounted for by assigning to the boron reaction an internal probability fifty times greater than that of the lithium reaction. Positive evidence as to whether or not the K-U upper limit is too high in this case will be obtained when the protons belonging to the reaction are identified.

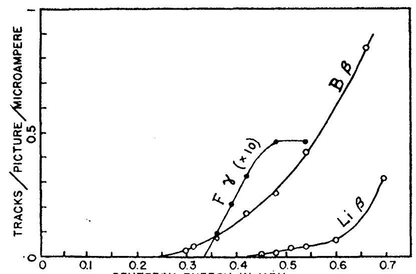
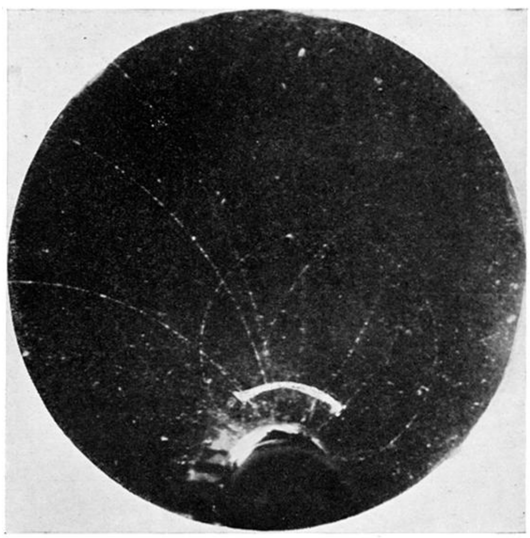


FIG. 8. Excitation curves for the reactions producing the Li and B beta-rays (unresolved ion beam). The voltage scale is calibrated by the excitation curve for the $F+H^1$ gamma-rays. For the beta-rays the solid angle subtended by the chamber window at the source was about $\pi/4000$.

It is clear from the excitation curves that the bombardment of boron with deuterons forms an excellent low voltage source of high energy electrons for experiments upon the electrons themselves. By bombarding with an unresolved ion beam of 100 microamperes at 300 kv, about 10^5 beta-rays per second can be obtained.

The authors wish to express their appreciation to the Rackham Endowment Fund for the support of this work.

[9]Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 504 (1936).



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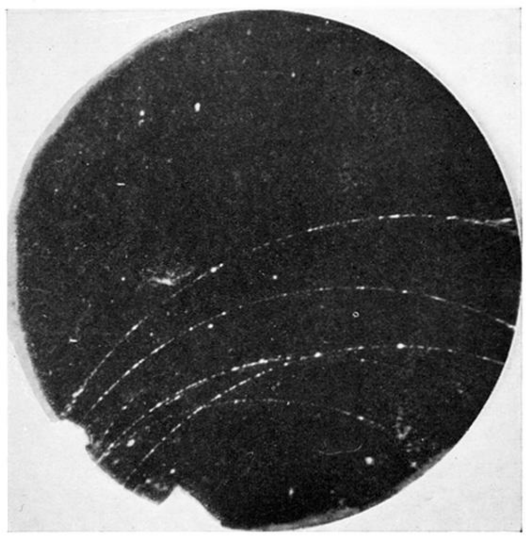

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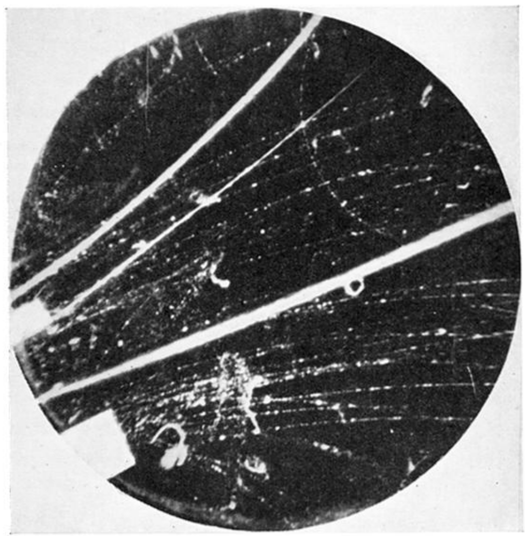

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