PROCEEDINGS OF THE ROYAL SOCIETY A | MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Some Experiments upon Artificial Transmutation Using the Cloud-Track Method

P. I. Dee

Proc. R. Soc. Lond. A 1935 **148**, 623-637
doi: 10.1098/rspa.1935.0037

Some Experiments upon Artificial Transmutation using the Cloud-track Method

By P. I. Dee, M.A., Sidney-Sussex College, Cambridge

(*Communicated by Lord Rutherford, O.M., F.R.S.—Received November* 1, 1934)

[Plates 24–27]

1—Introduction

The investigation of the disintegration particles which are emitted during the bombardment of the light elements by beams of artificially accelerated protons or diplons has been carried out at the Cavendish Laboratory by two main methods involving the use either of electrical counting devices or of an expansion chamber. While the counting methods are best suited for a rapid investigation of the types and ranges of the particles emitted from any particular element the cloud-track method, once the correct set of experimental conditions has been realized, gives direct evidence of the ranges and relative directions of emission of the particles resulting from a single nuclear process. The choice of this set of experimental conditions is greatly facilitated by a knowledge of the results of the "counting" experiments and therefore the expansion chamber method has been mainly used in these researches to provide a stringent test of the modes of transmutation suggested by the counting methods. An account is here presented of the investigation of (*a*) the transmutation effects produced by the bombardment of heavy hydrogen with diplons, and (*b*) the short range products which are emitted during the bombardment of lithium with protons. Summaries of the results of these experiments have already appeared: they are here described in greater detail.

2—Experimental Method

The short interval of time during which an expansion chamber is sensitive to incoming radiation makes it essential to use beams of bombarding ions of very high intensity. This requirement is further enhanced by the necessity of using very thin and small targets of the element under bombardment in order that the products originating at any point of the target may be recorded in whatever directions they may be emitted. It was therefore decided to replace the discharge tube used in the earlier researches of this nature by one which would be capable of producing more intense ion beams. The tube illustrated in fig. 1 has been suitable

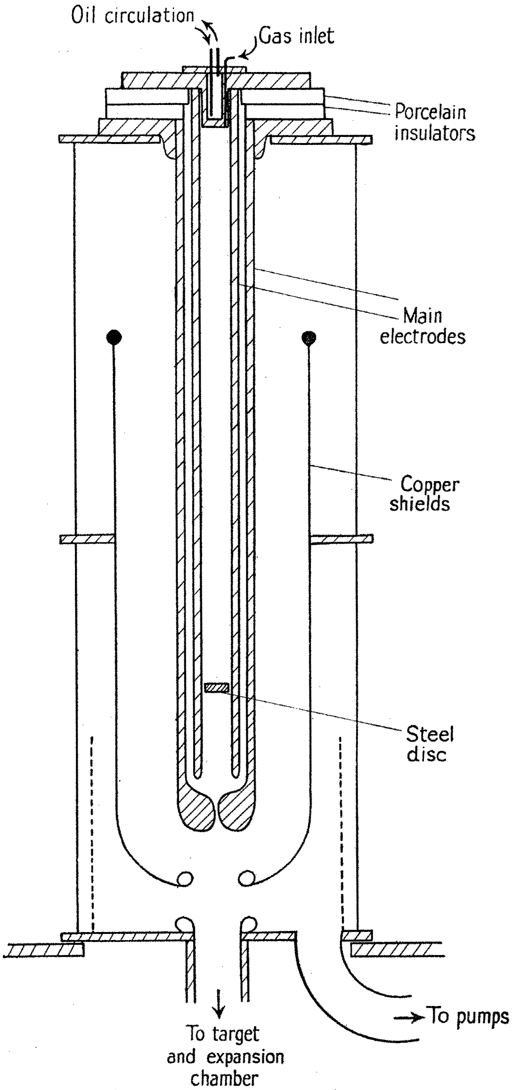

FIG. 1

for these experiments. In design it resembles closely the first tube used by Oliphant and Rutherford* for work at 250 kv, various modifications having been made for use at the higher voltages ($\sim$ 700 kv) available.

* 'Proc. Roy. Soc.,' A, vol. 141, p. 259 (1933).

The two main electrodes are steel cylinders of $\frac{1}{4}$-inch wall thickness screwed rigidly into two steel end pieces with flat porcelain discs as separating insulators. The clearance between the two tubes is from 9–11 mm over the whole length of the tubes (200 cm). It will be noticed that with this design the source of the ions is much nearer to the target than with the old design—the two accelerating gaps now being immediately adjacent. It is probable that the tube would be improved by the introduction of another metal cylinder in the position shown by the dotted lines, in order to protect the plasticene joint between the base of the lower glass cylinder and the base plate, and to reduce the electrical stresses in this neighbourhood, but the glass cylinders at present available have too small a diameter to permit its introduction. It has been found that up to 400 kv this tube is quite satisfactory but above that voltage much sparking occurs around the base of the lower glass cylinder. This sparking, however, may be prevented, by wrapping a wide sheet of semi-conducting paper around the base of this cylinder and voltages up to 600 kv may then be safely applied. Owing to the large mass and length of the discharge tubes it is possible to supply a large amount of energy to them without producing appreciable rise of temperature of any of the plasticene joints. It is unnecessary to apply oil cooling to the outer cylinder even for prolonged energy input of 5 kw. Some trouble was experienced in " out-gassing " the electrodes but since that was accomplished the tube has worked satisfactorily. A steel disc placed inside the inner electrode at about 25 cm from its lower end was found to be an improvement in that it raised slightly the working pressure of the gas in the tube. Before its introduction the adjustment of the leak through which hydrogen was supplied to the discharge tube had been inconveniently critical. The method of use is to apply the accelerating and discharge tube voltages, with the hydrogen leak closed and no current passing. Gas is then slowly admitted until the discharge tube " strikes " when the expansion chamber mechanism is fired. The gas leak is then closed until everything is ready for the next photograph. The expanson chamber and its subsidiary apparatus is essentially the same as was used in the earlier experiments.

3—The Bombardment of Heavy Hydrogen with Diplons

The first use of artificially accelerated diplons to produce atomic disintegration was made by Lawrence, Lewis and Livingstone* who reported that a proton group of 18 cm range was emitted from every

* ' Phys. Rev.,' vol. 44, p. 55 (1933).

element bombarded. Subsequent work by Cockcroft and Walton* showed that these results were due to contamination of the targets used and the discovery by Oliphant, Harteck and Rutherford†‡ that this group was emitted in enormous intensity when compounds containing heavy hydrogen were bombarded makes it certain that the results of the earlier workers should be explained by contamination of their targets with the heavy hydrogen used in the bombardment. It was shown further by Oliphant, Harteck and Rutherford that this emission of protons—of range 14 cm at their lower bombarding energies—was accompanied by the emission of a group of singly charged particles of range 1·6 cm and that the numbers of particles in the two groups were equal within the limits of measurement. They proposed for the nuclear process involved the reaction ${}_1H^2 + {}_1H^2 \rightarrow {}_1H^1 + {}_1H^3$, and showed that if the protons of mass 1 are associated with the observed range of 14 cm the range of the protons of mass 3 calculated by the application of the conservation of momentum would be in approximate agreement with the observed range of the shorter particles.

It follows from the application of momentum considerations to this process that these two particles would be emitted in opposite directions apart from the momentum of the incident diplon. (This latter correction leads, as we shall see later, to an angle between the two particles produced in the reaction of 162° for incident diplons of 160 e-kv energy.) To test the correctness of these views a photographic investigation was made by the author. A small tube of 1·0 cm diameter was introduced into the expansion chamber and connected to the main discharge tube as in the experiments previously described.§ A target consisting of a thin layer of heavy ammonium sulphate deposited upon thin mica was supported, at 30° to the vertical, at the lower end of this tube. On each side of this target was a plane supporting grid which carried mica windows through which the particles emitted during bombardment passed into the expansion chamber. These windows had stopping powers of 11·4 cm and 6·3 mm of air respectively and had to withstand the pressure of the gas in the chamber. The supporting grids were constructed so as to have high efficiency for passage of particles through them. The chamber was filled with an appropriate mixture of helium and air, stopping power varying from 0·3 to 0·4 in different experiments, so that the range in the gas of the 1·6 cm group after passage through the thin windows was about

* 'Proc. Roy. Soc.,' A, vol. 144, p. 704 (1934).
† 'Nature,' vol. 133, p. 413 (1934).
‡ 'Proc. Roy. Soc.,' A, vol. 144, p. 692 (1934).
§ Dee and Walton, 'Proc. Roy. Soc.,' A, vol. 141, p. 733 (1933).

3–4 cm. Under these conditions the majority of the longer proton tracks which passed through the thick window also stopped in the chamber.

The tracks were measured by replacing the plates in the cameras and reprojecting their images in space. The angle made by each track with the normal to the window through which it passed, its length and its inclination to the vertical were measured.

Examination of these photographs showed only very rarely obvious pairs of opposite tracks as were so frequently observed in the case of the earlier experiments when opposite pairs of 8·4 cm α-particles originated in the disintegration of lithium by protons (Dee and Walton, *loc. cit.*). This, however, is only to be expected on the hypothesis advanced since the light masses of the transmutation products in this case leads to the angle between the two tracks being about 162° for the bombarding voltage used, 160 kv. It is obvious therefore that in order to decide whether two tracks originate in the same nuclear process it is necessary to obtain photographs with very few tracks per expansion as otherwise, from probability considerations, there must be frequent occurrence of pairs with this angular separation.

A further test that any two tracks originate in the same transmutation may be made by examining whether they pass through a point. This latter consideration is, however, not very selective as the whole area of the target was only a few square millimetres, and the accuracy of reprojection of a track in space is not sensitive to much less than 0·5 mm.

It was decided, however, from this run of photographs that pairs of tracks passing through a point and with angular separation not less than 162° occurred about three to four times more frequently than would be the case solely as a result of probability.*

Occasionally pairs are observed in which the angle between the tracks is very near to 180°—this no doubt being the result of transmutations effected by slower diplons which have lost energy by collision in the target. Typical photographs obtained in this run are reproduced in figs. 8, 9, 10 and 11, Plates 25, 26. It was felt, however, that the above factor of 3–4 was not so high as might reasonably have been anticipated from considerations of the geometry of the window system employed.

An explanation of this fact was thought to lie in possible small deviations of the fast protons during their passage through the thick mica window, their original direction being incorrectly deduced from the direction of the last 2–3 cm of observed track. In order to examine this point further

* 'Nature,' vol. 133, p. 564 (1934).

sets of photographs were taken in which the 11·4 cm window was replaced by one of < 5 cm stopping power. This has the disadvantage that the long proton track does not end in the chamber so that the complete data of a transmutation cannot be obtained from a single photograph. Experiments under these conditions proved quite definitely that particles of about 1·6 cm range were opposite (angle $> 162°$) particles of range > 8 cm as frequently as the geometry of the windows would permit, and from other experiments it is quite certain that these tracks of range > 8 cm must in fact be the 14 cm group of the other workers. Examples of the photographs obtained under these conditions are given in figs. 6, 7, Plate 24. The reaction ${}_1H^2 + {}_1H^2 \rightarrow {}_1H^1 + {}_1H^3$ may, therefore, be regarded as definitely confirmed.

4—The Energy Balance in the Reaction

Before proceeding to a calculation of this energy balance in the reaction we will consider briefly the results to be anticipated from the application of the laws of conservation of energy and momentum to the process. Certain points of interest emerge which are of importance in accurate measurement, particularly in the calculation of the angle between the tracks which constitute a pair, and in the corrections for the energy of the bombarding particle.

Let the proton of mass 1 produced in the transmutation have velocity v_1 and make an angle θ_1 with the direction of the incident diplon of velocity v. Let v_3, θ_3 be the corresponding quantities for the particle of mass 3 which is produced.

Then it follows from the laws of energy and momentum that

$$v_1 = \tfrac{1}{2}\{v \cos \theta_1 \pm \sqrt{v^2 \cos^2 \theta_1 + 2(v^2 + 3E)}\},$$

where $E = Mc^2$, M = mass in gm, which is converted into kinetic energy in the process and $c = 3 \times 10^{10}$ cm/sec. This reduces approximately to a linear relation between v_1 and $\cos \theta_1$ for energies of the incident diplon less than 240 e-kv.

Similarly we have $v_3 = \frac{1}{2}\{v \cos \theta_3 \pm \sqrt{v^2 \cos^2 \theta_3 + \frac{2}{3}(E - v^2)}\}$ for the H^3 particle. Graphs showing the variation of v_1 with $\cos \theta_1$ and of v_3 with $\cos \theta_3$ are shown in fig. 2, for three bombarding energies.*

It will be noticed that increase of the energy of the bombarding particle results in a reduction in the range of the H^3 nucleus emitted at right angles to the incident beam. It is of interest to note that there are certain

* In these calculations E has been taken as 4×10^{18} corresponding to an energy liberation of $4 \cdot 1 \times 10^6$ electron volts.

angles near to 90° where there is very little change of velocity due to changes in the bombarding energy.

The energy of the H^1 particles emitted at right angles to the incident beam is $(\frac{3}{4}E + \frac{1}{4}W)$ while the energy of the H^3 particles emitted in the same direction is $(\frac{1}{4}E - \frac{1}{4}W)$. W = energy of incident diplon.

From these equations, for bombarding energy of 160 kv, we find that the range of the H^1 particles emitted in the direction of the incident

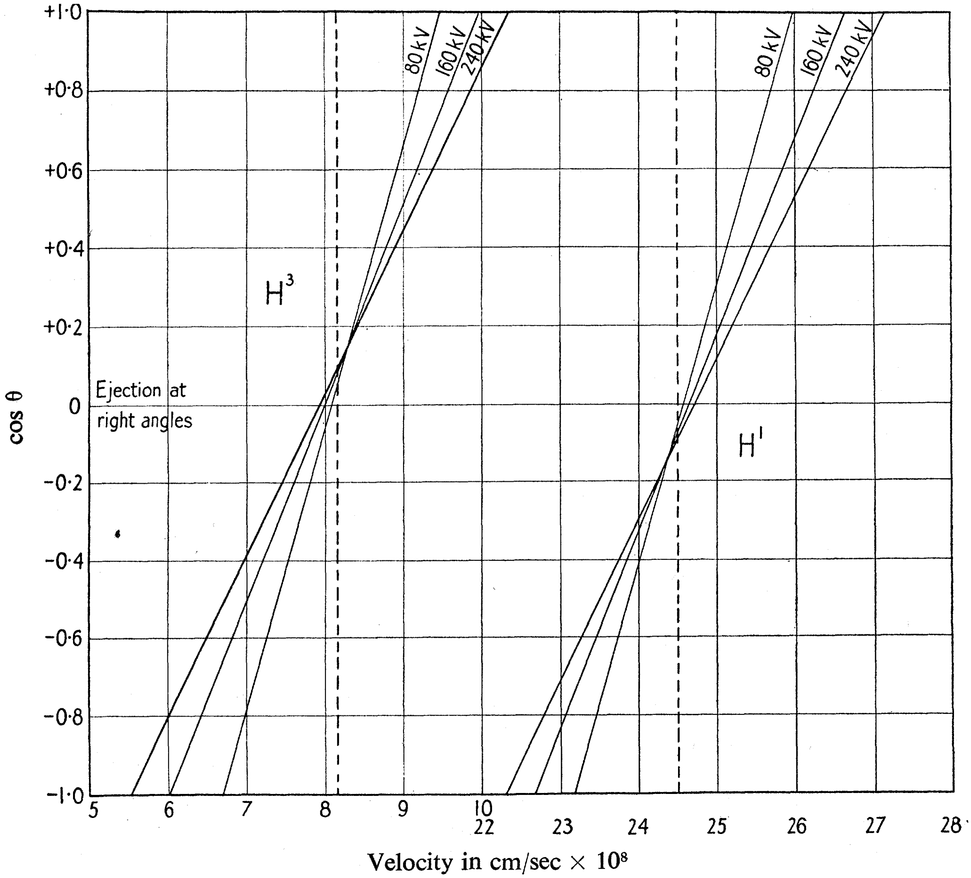

FIG. 2

diplons = 20·1 cm, in the reverse direction the range is 11·8 cm, while at right angles to the incident beam the range equals 15·5 cm. The ranges in the same directions for the H^3 particles are 3·2 cm, 0·8 cm and 1·7 cm.

It also follows from these calculations that the angle between the directions of emission of the two particles does not differ from 163° by more than 2° for all values of θ_1 from 60° to 120°. For other values of θ_1 this angle lies between 163° and 180°.

The photographs taken with the 6·3 mm and 11·4 cm windows showed a number of pairs of tracks passing through a point and with angular separations between 162° and 180°. As under these conditions each member of a pair ended in the chamber, measurement of the ranges gives for each pair a value for the total energy liberated in the process.

The mean value for the sum of the energies of the two tracks constituting a pair obtained in this way was 3·6 ± 0·3 million electron volts. In obtaining this figure no correction has been made for the loss of energy

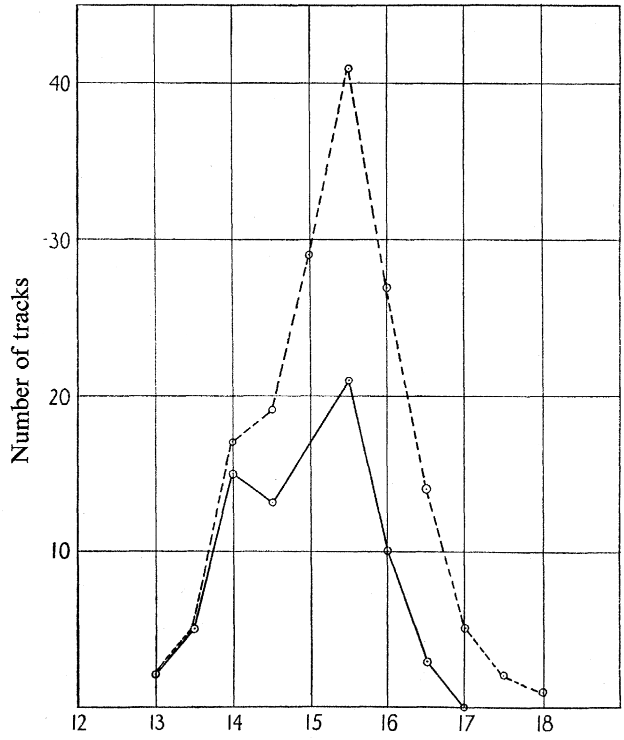

Fig. 3—H^1 particles. - - - Tracks observed from $\theta_1 = 60°$ to $90°$; —— tracks observed from $\theta_1 = 72°$ to $90°$.

which occurs in the passage of the particles through the layer of heavy ammonium sulphate used as a target. This layer consisted of a mass of small crytals and owing to its non-uniform character no accurate correction can be made for this energy loss. Rough measurements suggest, however, that the order of this correction would be about + 0·3 million electron volts.

A more accurate value for the energy balance may be obtained from the range frequency distributions of the particles, since, by taking the maximum ranges of each group, the effect of the finite target thickness may be eliminated.

The frequency-range distributions of the H^1 and H^3 particles are shown in figs. 3 and 4. An attempt has here been made to show the variation of the range of the particles with their direction of emission with respect to the diplon beam. For H^1 particles this change in maximum range

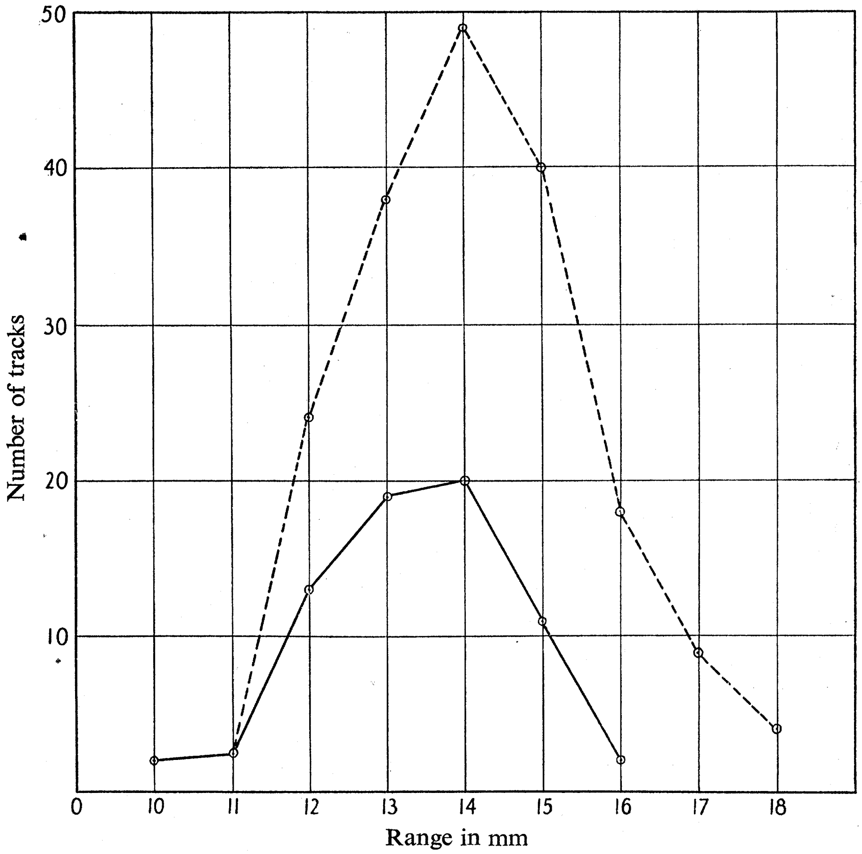

FIG. 4—H^3 particles. - - - Tracks observed from $\theta_3 = 60°$ to $90°$; —— tracks observed from $\theta_3 = 84°$ to $90°$

with θ_1 is in approximate agreement with that calculated in the above manner. The observed increase in range of the H^3 particles in the downward direction is much less than calculated, but it is believed that this is due to these greater ranges being overlooked, owing to the longer particles passing downwards out of the illuminated region of the chamber, whereas for the H^1 particles which are emitted downwards the effect of obliquity in the thick mica window is relatively much greater and partly compensates their increased range so that for these particles there is little alteration in their actual range in the gas.

It follows from these distributions that the range of the H^3 and H^1 particles emitted *at right angles* to the diplon beam are 16·0 mm and 15·7 cm respectively.

We therefore have $\frac{3}{4}E + \frac{1}{4}W$ = energy of a proton of mass 1 and range 15·7 cm = $3 \cdot 2 \times 10^6$ e-volts. Whence the energy of the H^3 particles emitted at right angles ($= \frac{1}{4}E - \frac{1}{4}W$) = $1 \cdot 0 \times 10^6$ e-volts corresponding to a range of 17·3 mm. The range velocity curve of Blackett and Lees* for slow protons has been used here. The observe range is 16·0 mm, in fair agreement with the calculated value considering the rapid variation of range with velocity for protons in this neighbourhood.

The ranges measured in these experiments after reduction to zero bombarding energy are for H^1 = 15·3 cm, for H^3 = 17·0 mm, and the corrected value for the energy liberated = $4 \cdot 2 \times 10^6$ e-volts, a value practically identical with that of Oliphant, Harteck and Rutherford.†

5—The Emission of Neutrons

It was suggested by Oliphant, Harteck and Rutherford‡ that the energy of the neutrons which they found to be emitted in the bombardment of heavy hydrogen with diplons was in approximate agreement with the proposed reaction ${}_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + {}_0n^1$, and as reported in 'Nature' (Dee, *loc. cit.*) an investigation of these neutrons using the expansion chamber led to a value for their maximum energy of $1 \cdot 8 \times 10^6$ e-volts. The value obtained by Oliphant, Harteck and Rutherford† from observations of the maximum size of the kicks produced by these neutrons in a linear counting chamber was about 2×10^6 e-volts. The expansion chamber investigation was made by replacing the target tube described in § 2 by a lead tube in which there was only one mica window a few square millimetres in area. A thick layer of heavy ammonium sulphate was placed in the bottom of this tube and bombarded with diplons of about 150 e-kv energy. Observation of the 15 cm protons which emerged through the small window enabled one to maintain correct working conditions.

The chamber was filled with 50% helium + 50% air and in a run of 150 photographs the tracks of 30 nuclei presumably recoiling from neutrons were photographed. The length of each recoil track and the

* 'Proc. Roy. Soc.,' A, vol. 134, p. 658 (1931).
† 'Proc. Roy. Soc.,' A, vol. 144, p. 692 (1934).
‡ 'Nature,' vol. 133, p. 413 (1934).

angle which it made with the line joining its origin to the target were measured by reprojection. The results are given in fig. 5 where the ranges have been reduced to N.T.P. The ranges of the recoil nitrogen nuclei are very small even in this diluted gas mixture.

Now for a neutron of mass n and velocity u incident upon a nucleus of mass M the recoil velocity of the heavy nucleus $= 2nu \cos \theta/(M + n)$, where θ = angle of projection of the nucleus relative to the direction of the incident neutron. Using this expression the full lines have been drawn to represent the range-angle distributions to be expected of helium nuclei (upper curve) and nitrogen nuclei (lower curve) for incident neutrons of energy $1 \cdot 9 \times 10^6$ e-volts. The horizontal lines represent the lower limits

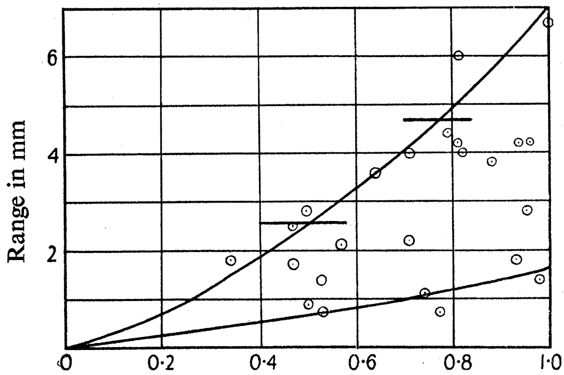

FIG. 5

of the estimated errors of these observations. While the actual ranges for the helium recoil nuclei are probably accurate to 5% the estimation of the direction relative to the incident neutron is often difficult to determine especially for the shorter tracks.

The results suggest that the neutrons may be homogeneous and of this energy. For the reaction ${}_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + {}_0n^1$ using the value for the mass of ${}_2He^3 = 3 \cdot 0163 \pm 0 \cdot 0004$ obtained by Rutherford and Oliphant, of the neutron* $= 1 \cdot 0080 \pm 0 \cdot 0005$ and of ${}_1H^2 = 2 \cdot 0136 \pm 0 \cdot 0001$,† we obtain for the total energy liberated in the reaction $0 \cdot 0029 \pm 0 \cdot 0006$ mass units and hence a value $0 \cdot 0021 \pm 0 \cdot 0004$ mass units $= 1 \cdot 9 \pm 0 \cdot 4 \times 10^6$ e-volts for the energy of the neutrons.‡

* Chadwick and Goldhaber, 'Nature,' vol. 134, p. 237 (August, 1934).

† Bainbridge, 'Phys. Rev.,' vol. 44, p. 56 (1933).

‡ Throughout the paper atomic masses are used in the equations—this does not lead to error in the calculation of the energy changes for the reactions considered.

The observed value for the maximum neutron energy of $1 \cdot 9 \times 10^6$ e-volts after correction for the energy of the bombarding particles (= 500 e-kv) is $1 \cdot 8 \times 10^6$ e-volts (see § 4) in excellent agreement with the calculated value. (The neutrons observed were those emitted approximately at right angles to the diplon beam, and the results of the measurements of individual recoil tracks do not seem to justify more than this general correction.)

A recoil nucleus of helium photographed under these conditions is shown in fig. 12, Plate 27.

On one of these photographs a forked track starting in the gas was observed, the plane of which passed through the source and hence might be attributed to the disintegration of a nitrogen nucleus effected by a neutron.

Assuming the reaction to be ${}_7N^{14} + {}_0n^1 \rightarrow {}_2He^4 + {}_5B^{11}$ (the type investigated by Feather) the ranges of the particles were shown to be in approximate agreement with this hypothesis and calculation showed that an energy of $0 \cdot 7 \times 10^6$ e-volts was liberated in the process. The α-particle track had a reduced range of 11 mm, and made an angle with the direction of the incident neutron of 52°. The ${}_5B^{11}$ nucleus was emitted nearly at right angles to the neutron direction and hence enters only as a small correction in the balance of the forward momentum. From the latter balance therefore a good accuracy can be expected in the calculated neutron energy and the figure thus obtained was $1 \cdot 9 \times 10^6$ e-volts in good agreement with the rest of this work. Substitution of the masses in the above reaction leads to an expected energy release of $2 \cdot 6 \times 10^6$ volts so that it must be assumed that the resulting ${}_5B^{11}$ nucleus is excited to a level of $1 \cdot 9 \times 10^6$ volts. Evidence of such a level has been obtained by Cockcroft and Walton from the protons emitted in the reaction

$$ {}_5B^{10} + {}_1H^2 \rightarrow {}_5B^{11} + {}_1H^1.* $$

6—The Short Range Products of the Disintegration of Lithium by Protons

The early work of Cockcroft and Walton* showed that in the bombardment of lithium with protons a group of particles of range < 2 cm was produced in addition to the 8·4 cm group of α-particles resulting from the reaction ${}_3Li^7 + {}_1H^1 \rightarrow 2{}_2He^4$. It was shown by Oliphant, Kinsey and Rutherford† that these particles constituted two groups of ranges 11·5

* Cockcroft and Walton, 'Proc. Roy. Soc.,' A, vol. 144, p. 704 (1934).

† 'Nature,' vol. 131, p. 23 (1933).

‡ 'Proc. Roy. Soc.,' A, vol. 141, p. 722 (1933).

and 6–8 mm, and in an expansion chamber investigation by the author* evidence was obtained which strongly suggested that these short range particles were emitted in opposite pairs. Some evidence of this fact has also been obtained by Kirchner.† On showing further that the 11·5 mm particles were emitted from the $_3Li^6$ isotope‡ Oliphant, Harteck and Rutherford have proposed for the reaction the nuclear process

$$_3Li^6 + {_1H^1} \rightarrow {_2He^3} + {_2He^4},$$

the range of the two groups approximately satisfying the application of the momentum relations.

In the expansion chamber investigation of this process a new method was employed, since, for particles of range as short as these, the method of bombarding a target *in vacuo* and allowing the products of disintegration to pass into the expansion chamber through mica windows is unsatisfactory. The mica windows which may be used cannot be more than 3–4 mm air equivalent in order to leave a reasonable length of track in the chamber and since these mica sheets must support the gas pressure in the chamber it is difficult to mount them upon grids which have a high efficiency for other than normally incident particles. To overcome this difficulty the proton beam has been made to pass through a thin mica window into the expansion chamber and there to be incident upon a thin inclined lithium target a few millimetres from their place of entry. For this purpose the end of a small tube was drilled with about 100 holes each 0·3 mm diameter and covered with a piece of mica of 2·5 mm air equivalent.

The target was a layer of lithium oxide deposited on a sheet of aluminium, the whole being equivalent to 3·0 mm of air. A typical photograph is shown in fig. 13, Plate 27.

The dense sphere at the end of the tube is due to condensation upon the ions produced by the entering protons while a pair of opposite short range particles are observed and end in the chamber.

The disadvantage of this method is the loss of intensity of the beam incident upon the target and the short time of registration of tracks in the chamber when so much ionization is produced. There is also usually present a large amount of general ionization throughout the chamber due possibly to the emission of soft radiation near the target. Even under these conditions opposite pairs cannot be expected in every case as

* 'Rept. Brit. Ass.,' (September, 1933), and 'Nature,' vol. 132, p. 818 (1933).

† 'Phys. Z.,' vol. 34, p. 777 (1933).

‡ Oliphant, Shire and Crowther, 'Nature,' vol. 133, p. 377 (1934).

occasionally the direction of motion of a particle is such that it passes so obliquely through the target that its residual range is insufficient to enable it to show beyond the sphere of scattered protons. A great advantage lies, however, in the fact that this reduction of range is calculable from the target thickness and the absence of a particle opposite to an observed particle can often be attributed to this reason. Where the particles have to pass through a grid supporting a mica window it is impossible to decide whether the absence of a particle opposite an observed one is due to its having struck a part of the grid, or to the possibility that the process investigated does not give rise to particles ejected in opposite pairs. Of 22 tracks photographed under these conditions in a run of 150 expansions 14 occurred in nearly opposite pairs and of the remaining 8, 5 were emitted in such directions that corresponding opposite tracks would have had equivalent paths in the target greater than the maximum range of the observed particles.

The values for the sum of the ranges of the members of a pair + the equivalent path in the target reduced to air at N.T.P. were 21·1, 20·4 22·2, 22·0, 20·0 (26·6, 28·7). It is impossible to draw any accurate conclusion as to the individual ranges owing to the finite thickness of the lithium oxide layer. The maximum observed range was 12·0 mm. Assuming this to be due to a $_2He^3$ particle its velocity $= 1\cdot2 \times 10^9$ cm/sec whence the velocity of a $_2He^4$ nucleus emitted in the opposite direction would be $0\cdot9 \times 10^9$ cm/sec corresponding to a range = 9·5 mm. Thus the sum of the ranges of the two particles might be expected to be 21·5 mm agreeing well with five of the observed values. The total energy liberated from these figures $= 3\cdot8 \times 10^6$ e-volts, or after correction for the energy of the incident proton $= 3\cdot5 \times 10^6$ e-volts. This figure agrees reasonably well with that of Oliphant, Harteck and Rutherford and as they have shown* leads to a mass for $_2He^3$ of $3\cdot0163 \pm 0\cdot0004$.

The above explanations seem, however, to be further complicated by the observation of Kirchner and Neuert† that the short range products of this transformation seem to constitute three groups of ranges 7, 9 and 12 mm, since they leave the 7 mm group without explanation. Crane and Lauritsen‡ have attempted to explain a third group by assuming a possible excitation of a γ-ray of 12×10^6 e-volts such a γ-ray having been shown by them to be present at their higher voltages. But this explanation would seem to be invalidated by the work of Oliphant and

* Blackett and Lees, ‘Proc. Roy. Soc.,’ A, vol. 134, p. 658 (1931).

† ‘Phys. Z.,’ vol. 7, p. 292 (1934).

‡ ‘Rept. Int. Phys. Congress London’ (October, 1934).

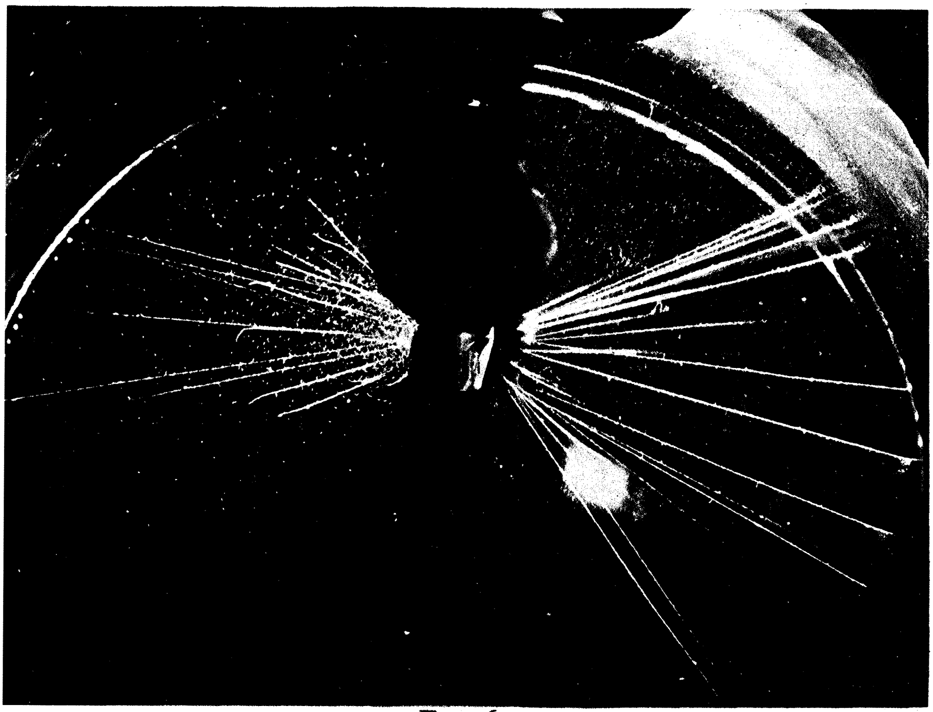

FIG. 6

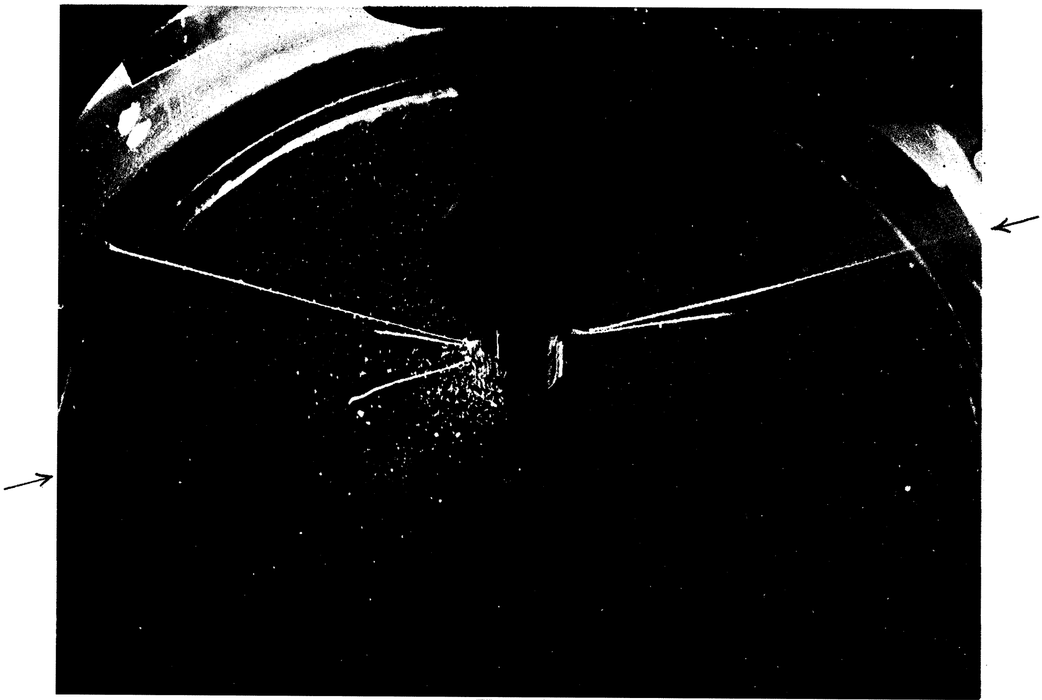

FIG. 7

FIG. 6—The 1·7 cm group of H^3 nuclei is seen on the left of the target tube. The proton tracks which pass through the right-hand window have passed out of the chamber and have a range of more than 8 cm

FIG. 7—A photograph showing an H^3 particle opposite a track which passes out of the chamber on the right and which has a range > 8 cm

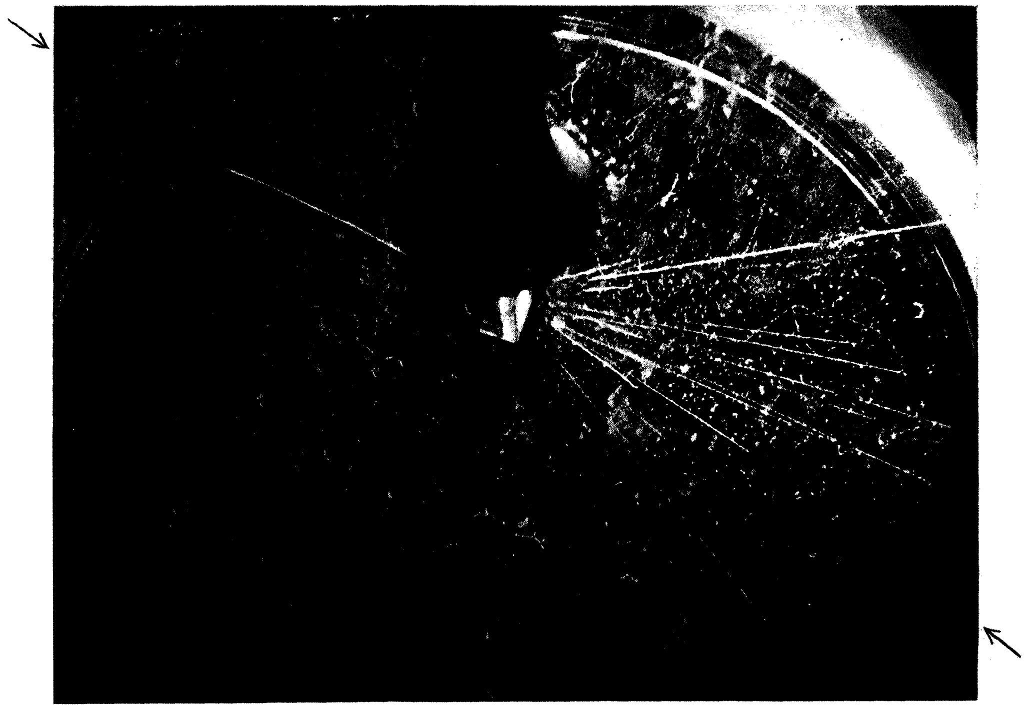

FIG. 8

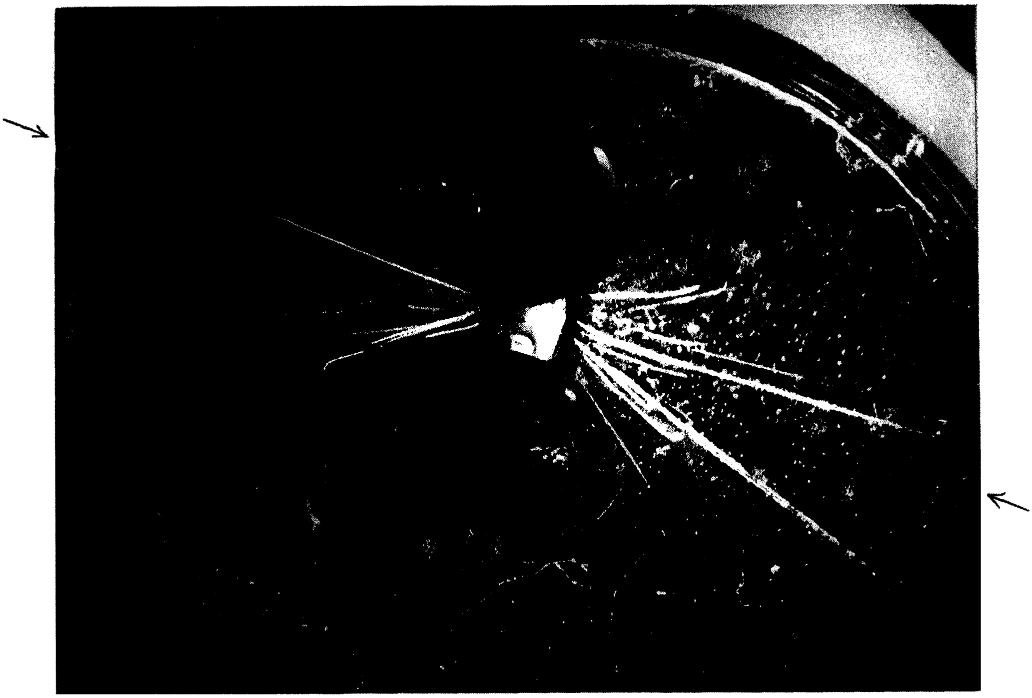

FIG. 9

FIGS. 8–11—Examples of the emission in nearly opposite directions of H^1 and H^3 particles arising in the reaction ${}_1H^2 + {}_1H^2 \rightarrow {}_1H^1 + {}_1H^3$. The 15 cm proton tracks are on the left of the target tube and end in the chamber since in these cases an 11·4 cm mica window was used. The short tracks which emerge on the right have passed through a mica window of 6·3 mm stopping power. The long tracks on the right passing out of the chamber are due to 15 cm protons emitted in this direction

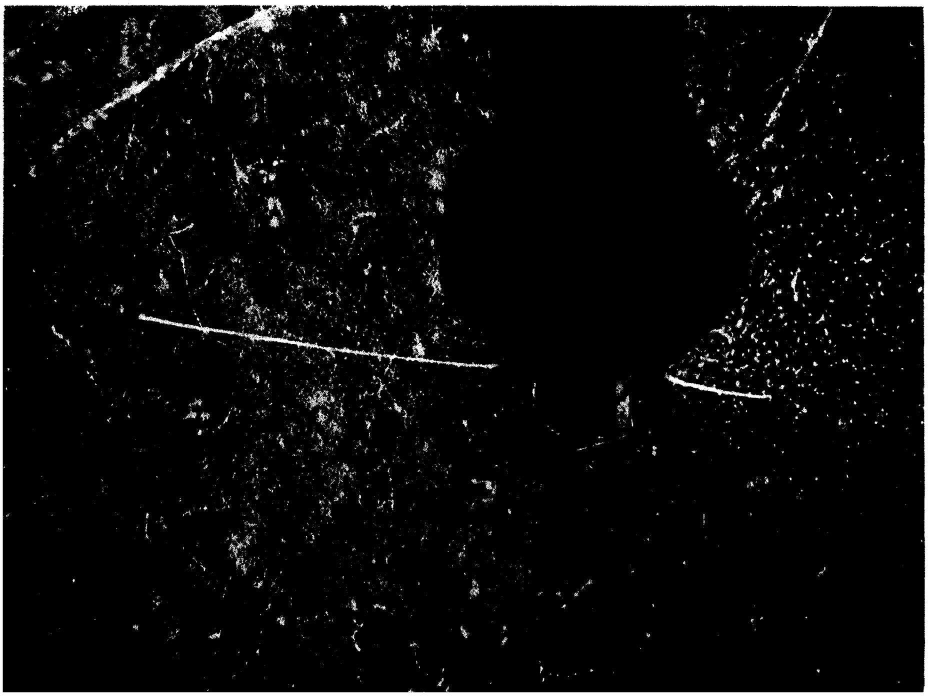

FIG. 10

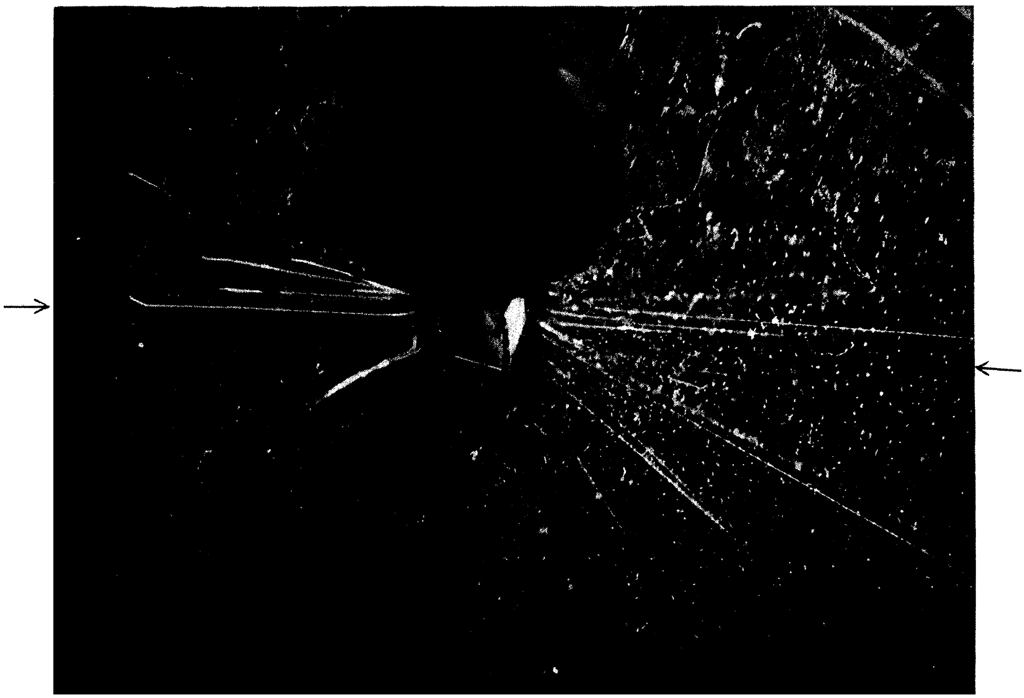

FIG. 11

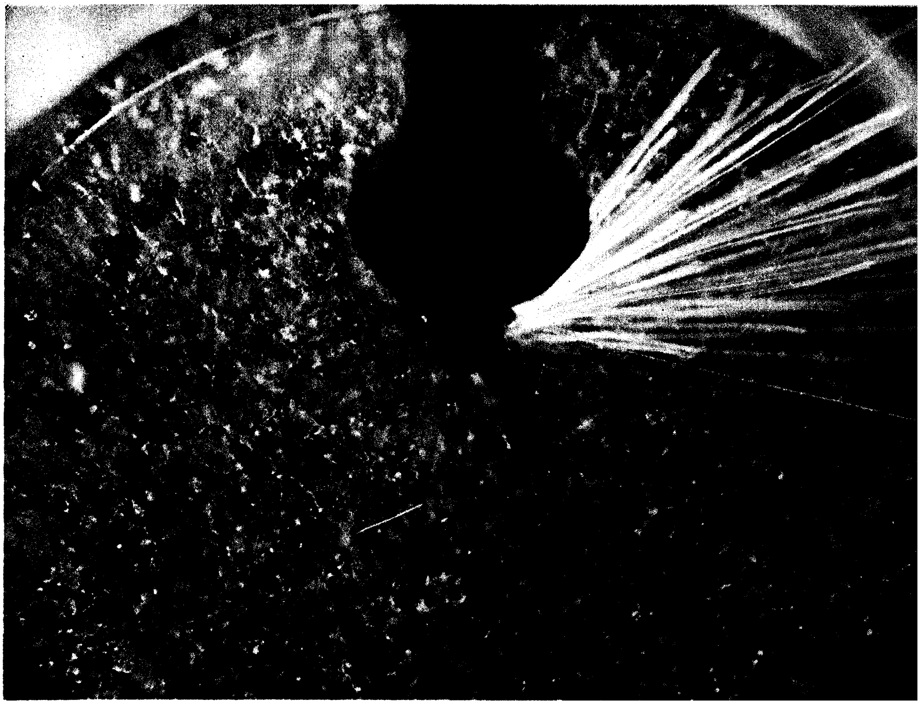

FIG. 12

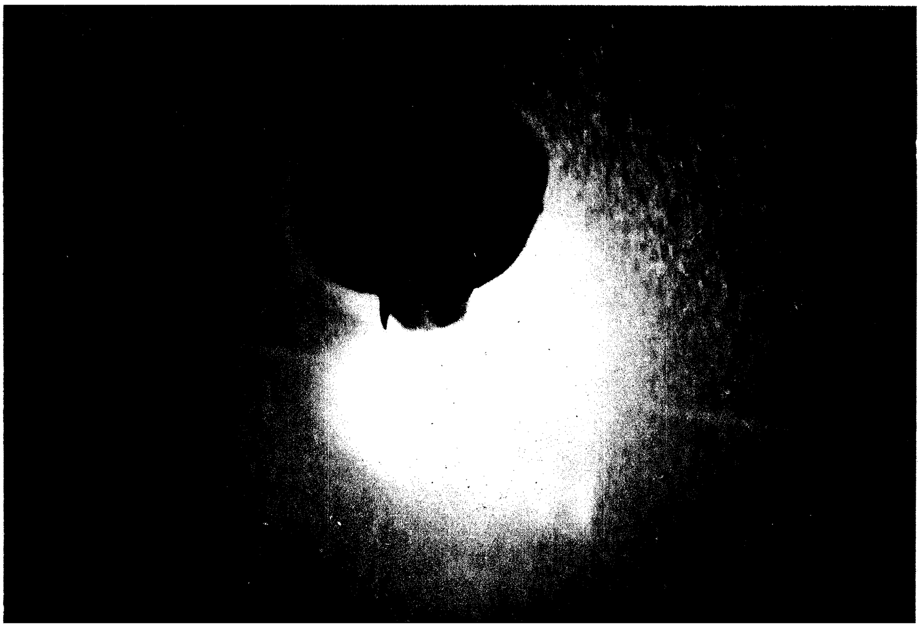

FIG. 13

FIG. 12—A nucleus of helium recoiling from a neutron originating in the target. On the right a group of 15 cm protons emerge through a small window in the target tube

FIG. 13—The white sphere around the end of the target tube is due to the proton beam entering the gas. An opposite pair of particles emitted from a lithium target near the end of this tube corresponds to the reaction ${}_3Li^6 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^3$

Westcott (unpublished), who have shown that there is no appreciable amount of γ-radiation produced in this process at the low bombarding energies used in their experiments and in those of Kirchner.

Throughout this paper the range velocity data for protons and α-particles has been taken from a set of curves issued to the laboratory by Duncanson and Feather. These curves were contructed from a collection and revision of the data at present existing.

The high voltages used in these researches were obtained from apparatus installed at the Cavendish Laboratory by Cockcroft and Walton.

I wish to express my gratitude to Lord Rutherford for his continued interest and encouragement. I am indebted to Dr. Oliphant for much advice in the design of the new discharge tube. Finally, I wish to thank Mr. Birtwhistle for his assistance throughout the whole of the work.

Summary

A study has been made of the tracks produced in a cloud-chamber when heavy hydrogen is bombarded by artificially accelerated diplons. It has been found that the products of the transformation are emitted in opposite pairs of ranges 15·3 and 1·7 cm respectively. This is in accordance with the reaction

$$ {}_1H^2 + {}_1H^2 \rightarrow {}_1H^1 + {}_1H^3 $$

when momentum and energy are conserved. An examination has been made of the effect of the speed of the bombarding diplons on the ranges of the particles appearing in the transformation.

An investigation of the neutron emission during the same bombardment from photographs of the tracks of recoiling nuclei gives an energy value for the neutrons of $1 \cdot 8 \times 10^6$ e-volts. The short range products of the disintegration of lithium by protons have also been studied with the expansion chamber. Strong evidence in favour of the reaction

$$ {}_3Li^6 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^3 $$

has been obtained since the products are shown to be emitted in opposite pairs and the ranges to be in agreement with the energy balance of the reaction.

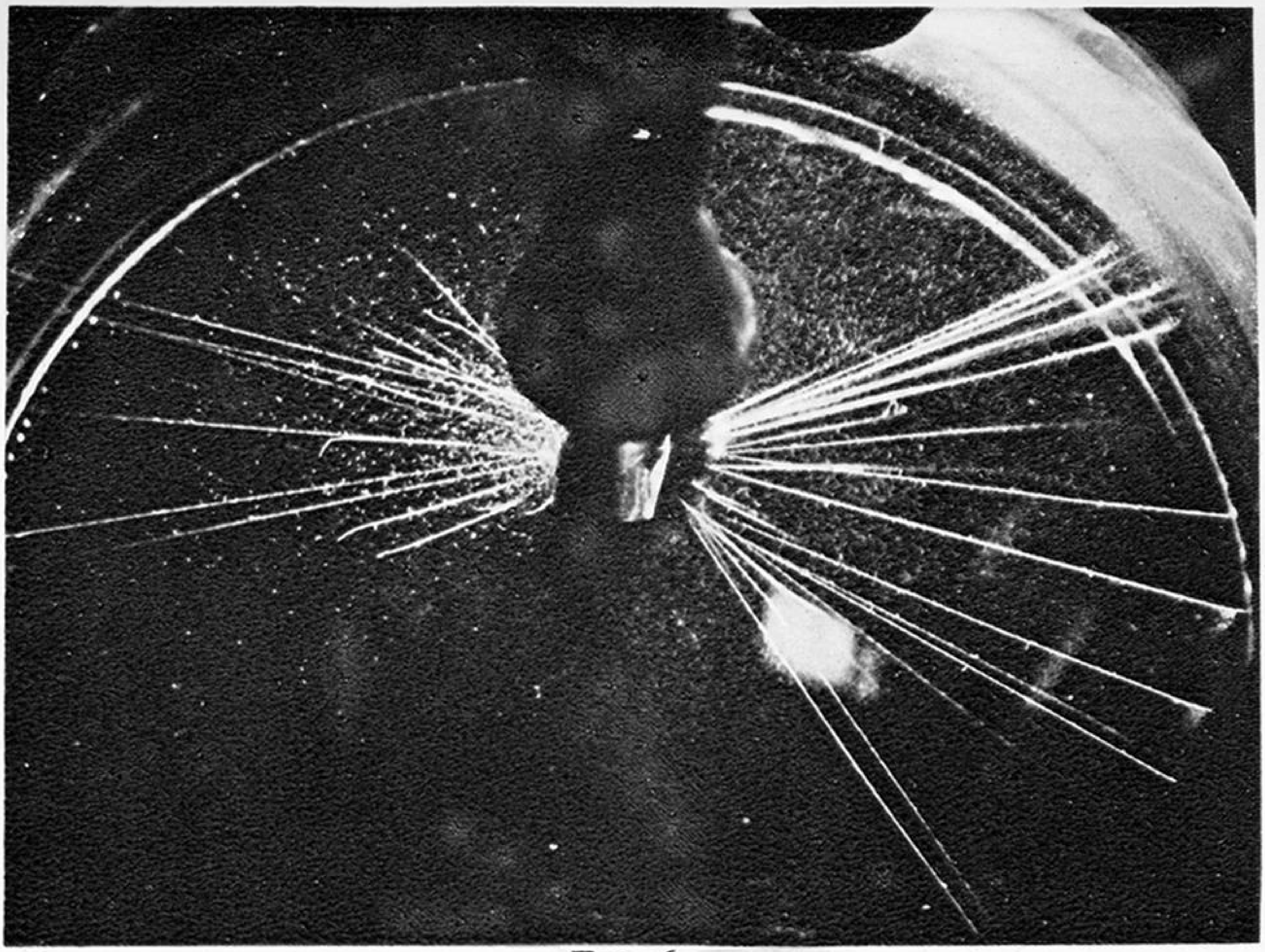

FIG. 6

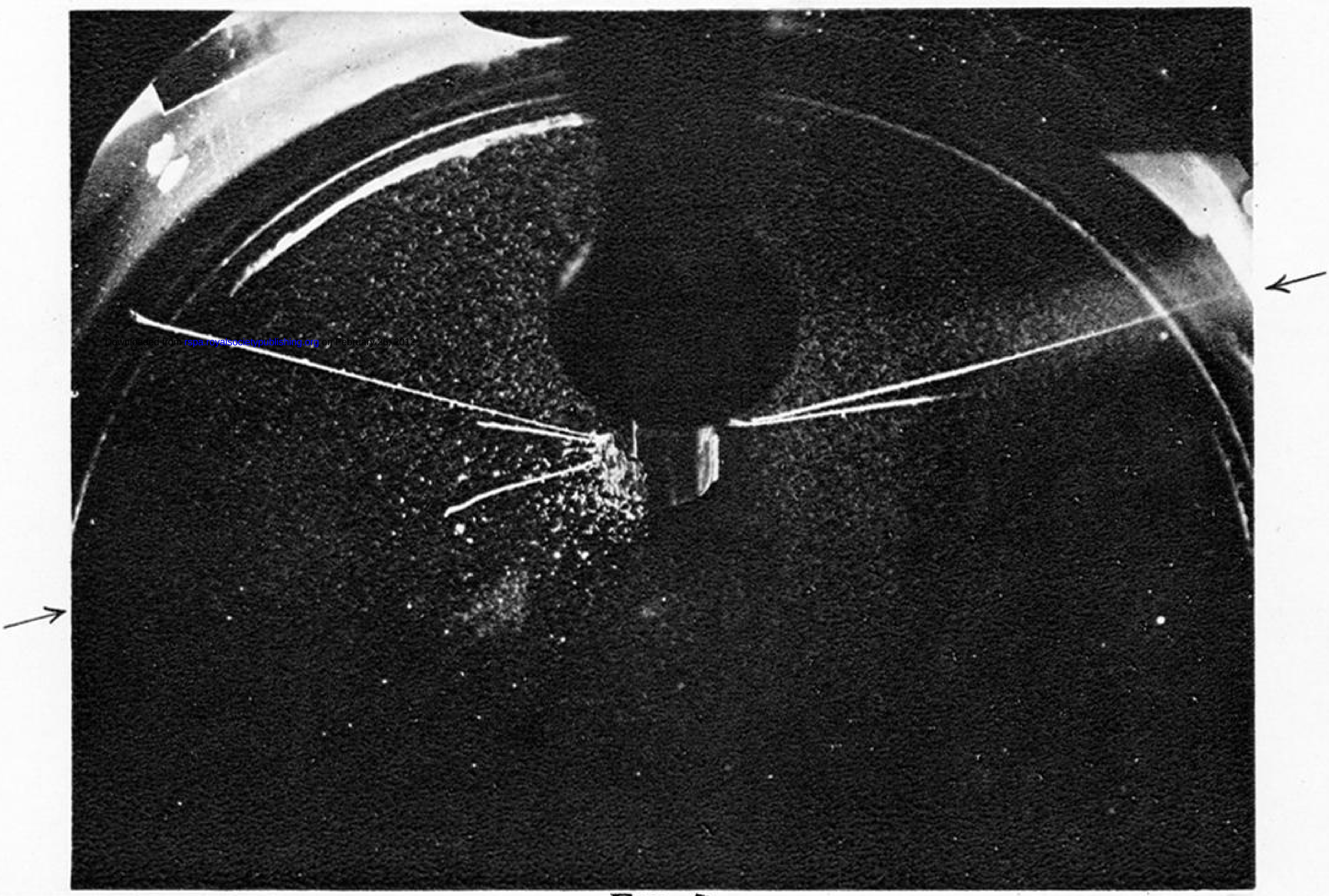

FIG. 7

FIG. 6—The 1·7 cm group of H^3 nuclei is seen on the left of the target tube. The proton tracks which pass through the right-hand window have passed out of the chamber and have a range of more than 8 cm

FIG. 7—A photograph showing an H^3 particle opposite a track which passes out of the chamber on the right and which has a range $>$ 8 cm

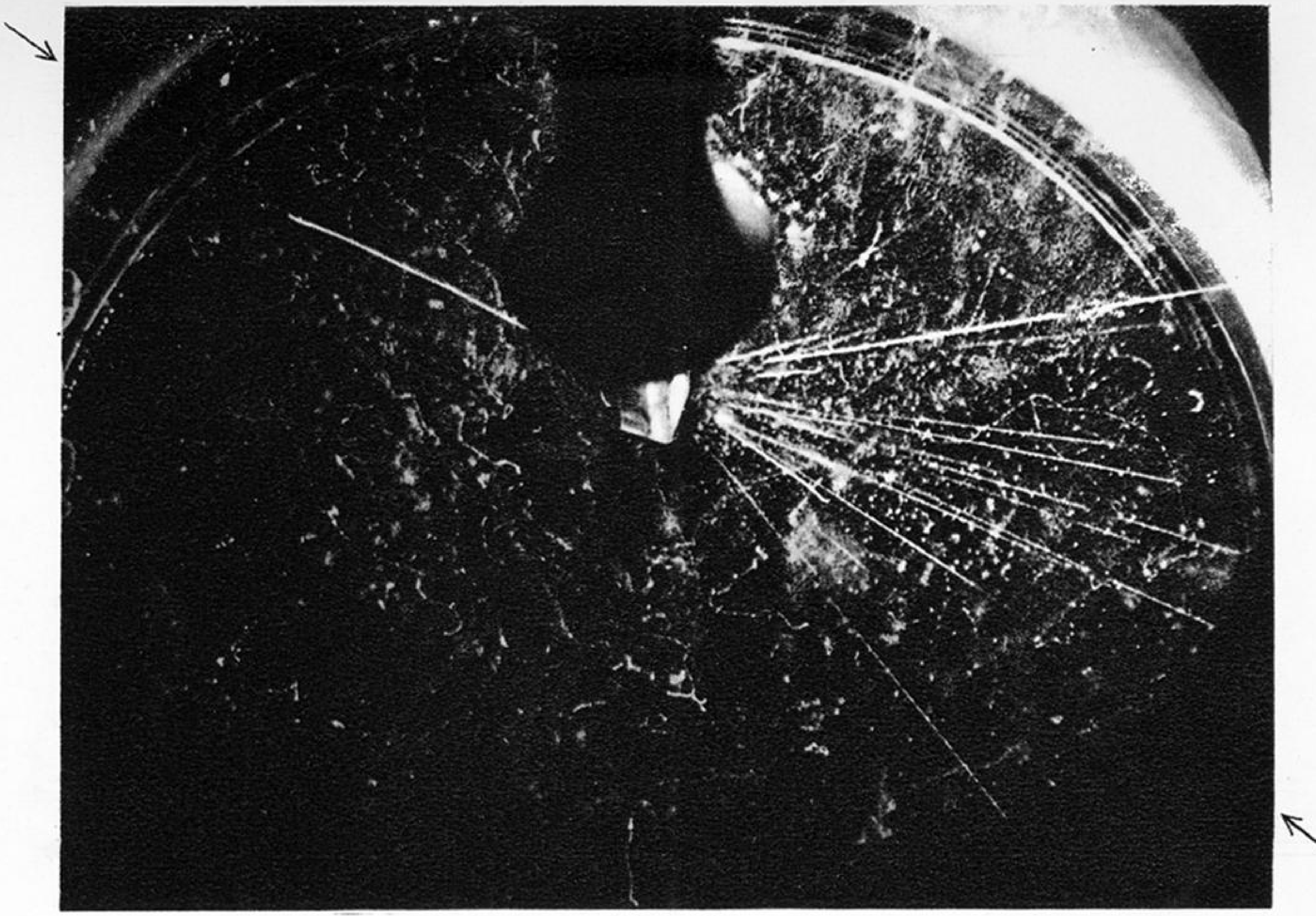

FIG. 8

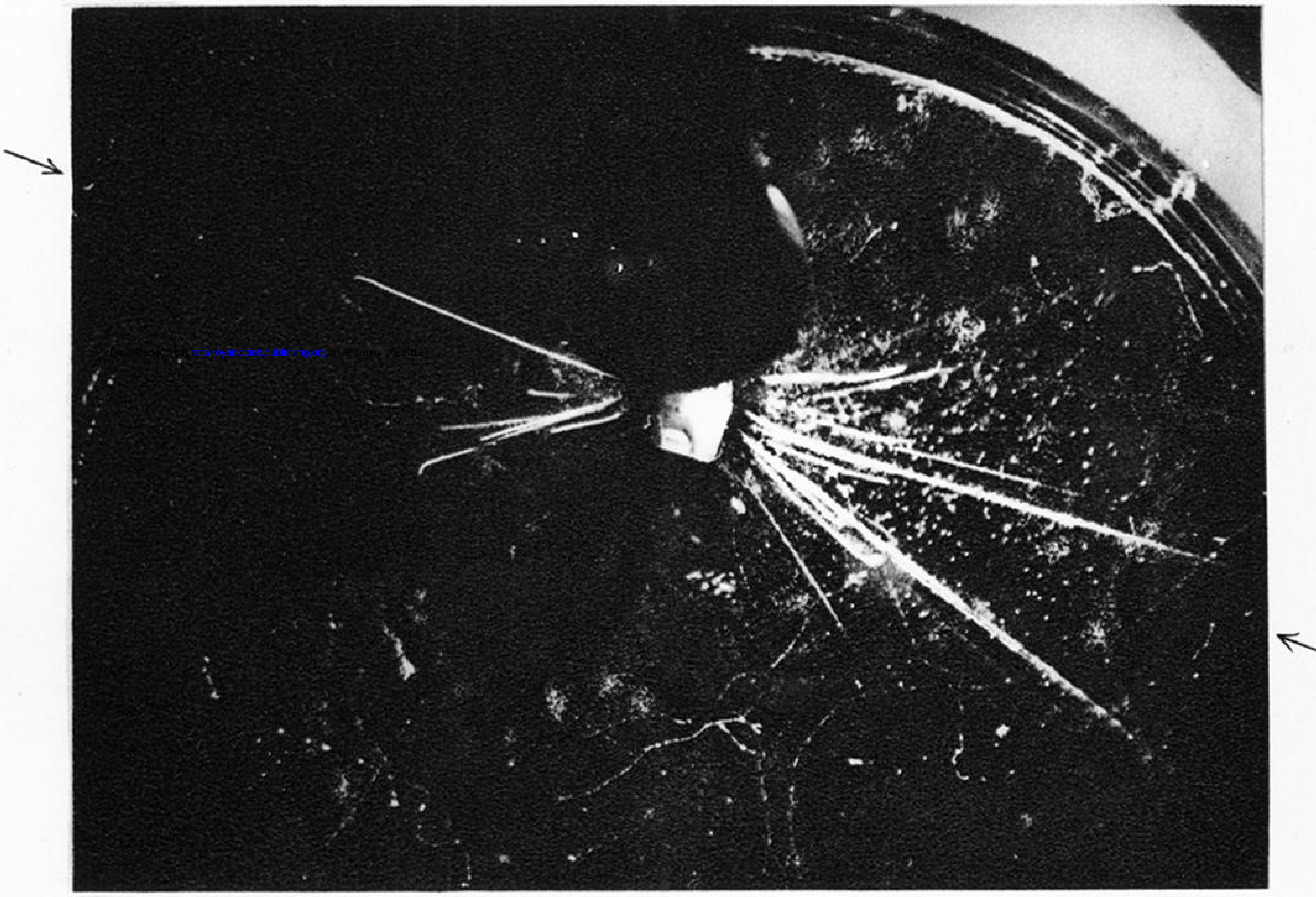

FIG. 9

FIGS. 8–11—Examples of the emission in nearly opposite directions of H^1 and H^3 particles arising in the reaction ${}_1H^2 + {}_1H^2 \rightarrow {}_1H^1 + {}_1H^3$. The 15 cm proton tracks are on the left of the target tube and end in the chamber since in these cases an 11·4 cm mica window was used. The short tracks which emerge on the right have passed through a mica window of 6·3 mm stopping power. The long tracks on the right passing out of the chamber are due to 15 cm protons emitted in this direction

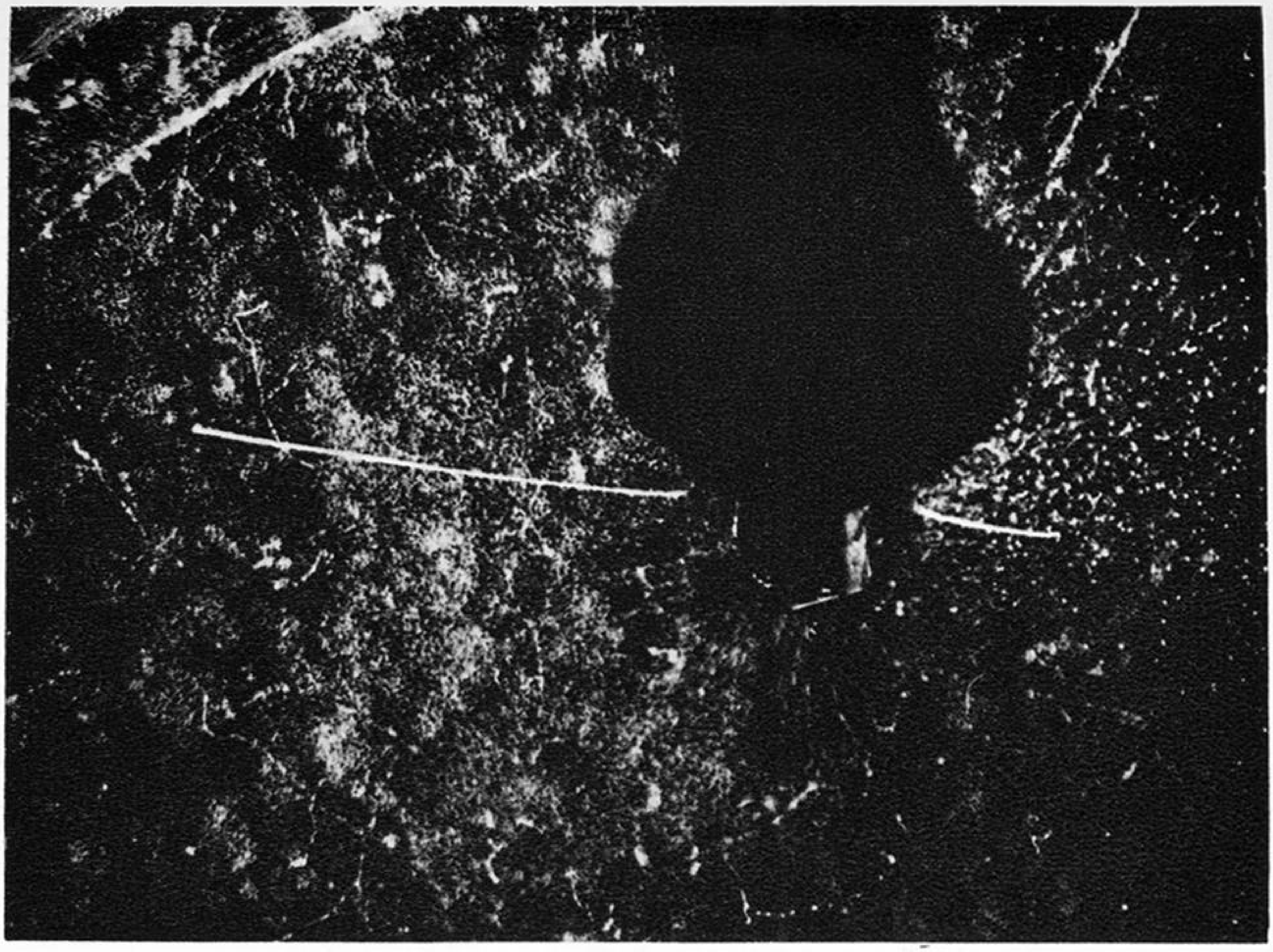

FIG. 10

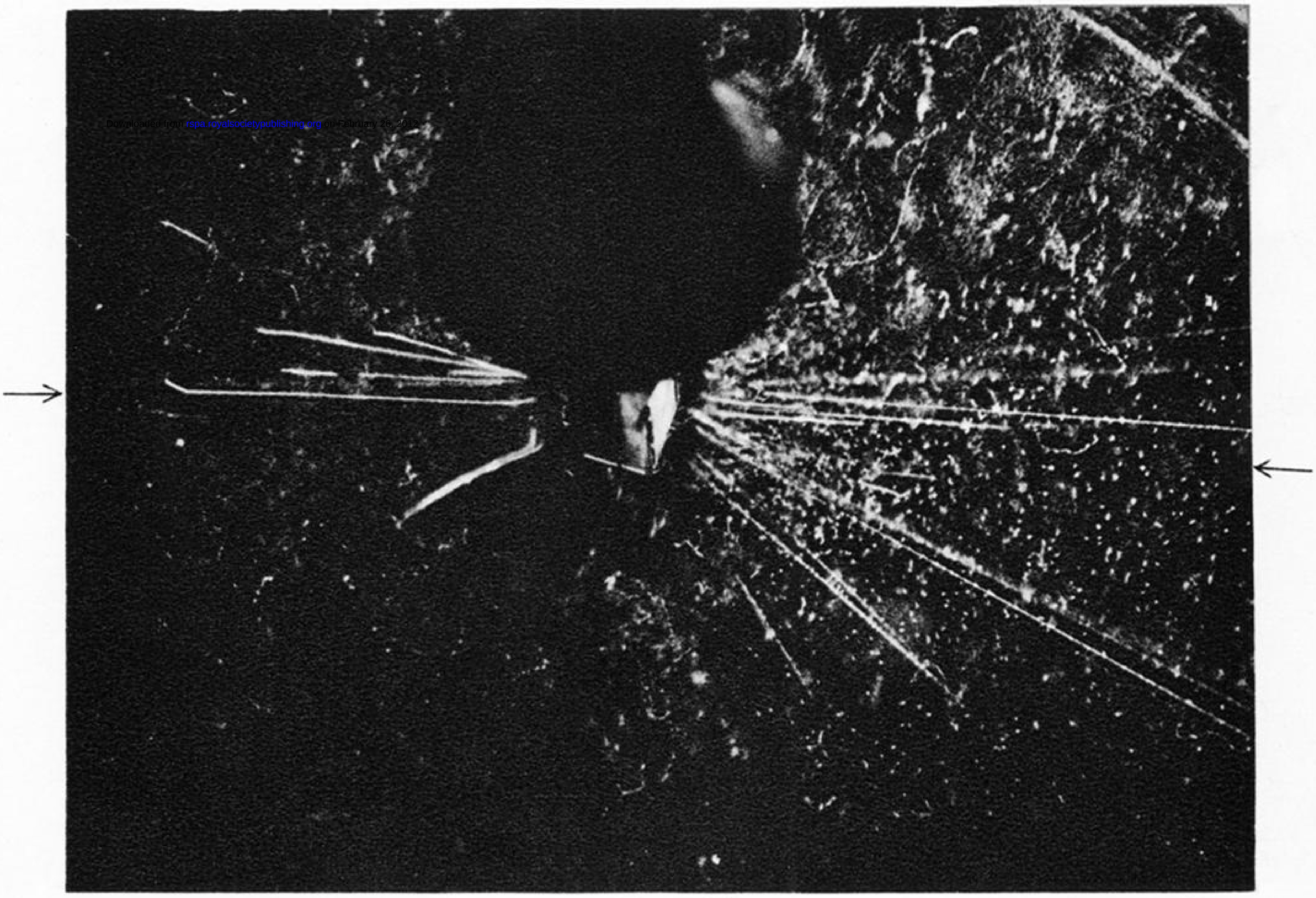

FIG. 11

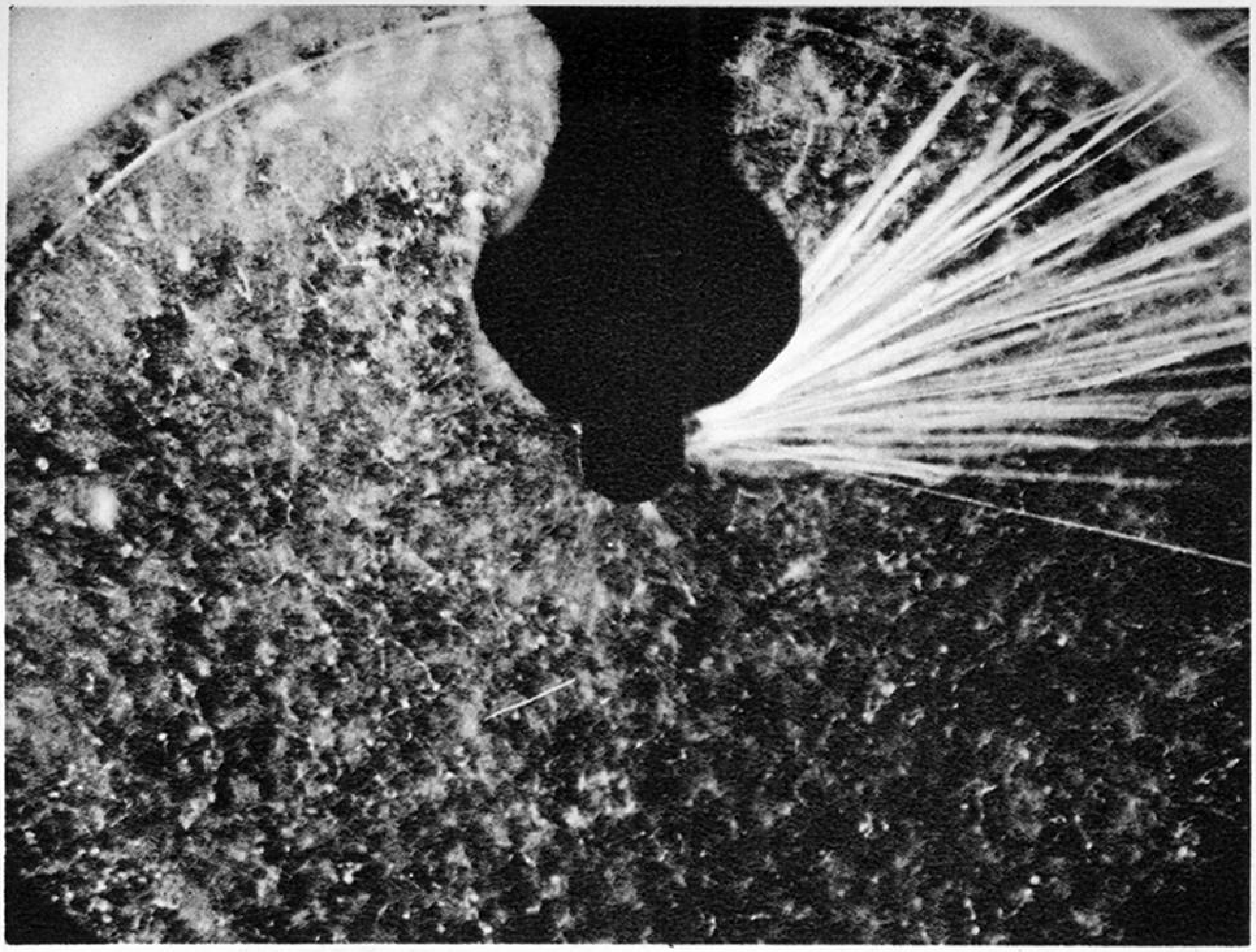

FIG. 12

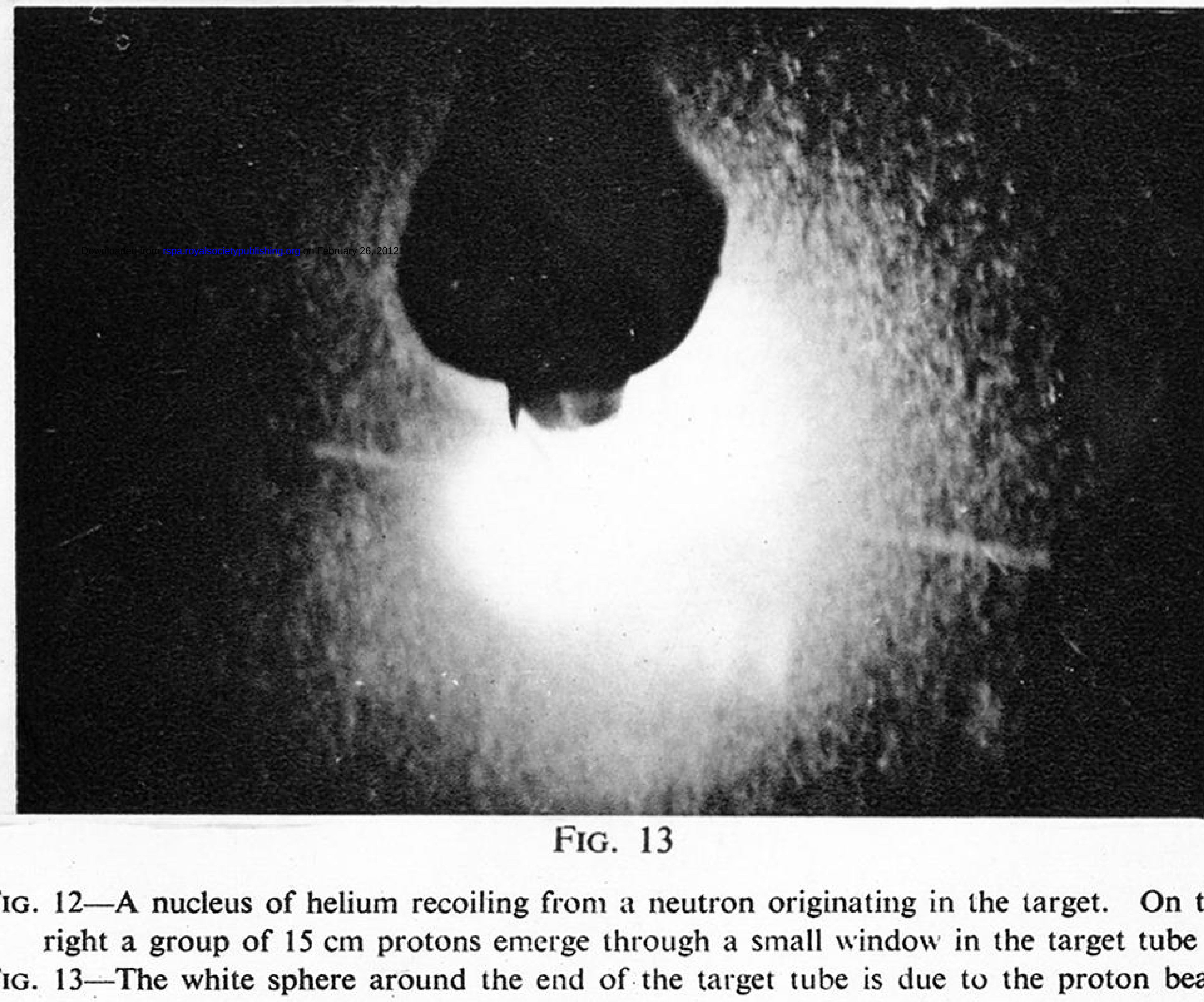

FIG. 13

FIG. 12—A nucleus of helium recoiling from a neutron originating in the target. On the right a group of 15 cm protons emerge through a small window in the target tube

FIG. 13—The white sphere around the end of the target tube is due to the proton beam entering the gas. An opposite pair of particles emitted from a lithium target near the end of this tube corresponds to the reaction ${}_{3}Li^{6} + {}_{1}H^{1} \rightarrow {}_{2}He^{4} + {}_{2}He^{3}$