On an Expansion Apparatus for making Visible the Tracks of Ionising Particles in Gases and some Results obtained by its Use.

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[Plates 6—9.]

In a recent communication* I described a method of making visible the tracks of ionising particles through a moist gas by condensing water upon the ions immediately after their liberation. At that time I had only succeeded in obtaining photographs of the clouds condensed on the ions produced along the tracks of α-particles and of the corpuscles set free by the passage of X-rays through the gas. The interpretation of the photographs was complicated to a certain extent by distortion arising from the position which the camera occupied.

The expansion apparatus and the method of illuminating the clouds have both been improved in detail, and it has now been found possible to photograph the tracks of even the fastest β-particles, the individual ions being rendered visible. In the photographs of the X-ray clouds the drops in many of the tracks are also individually visible; the clouds found in the α-ray tracks are generally too dense to be resolved into drops. The photographs are now free from distortion. The cloud chamber has been greatly increased in size; it is now wide enough to give ample room for the longest α-ray, and high enough to admit of a horizontal beam of X-rays being sent through it without any risk of complications due to the proximity of the roof and floor.

The Expansion Apparatus.

The essential features of the expansion apparatus are shown in fig. 1. The cylindrical cloud chamber A is 16·5 cm. in diameter and 3·4 cm. high; the roof, walls and floor are of glass, coated inside with gelatine, that on the floor being blackened by adding a little Indian ink. The plate glass floor is fixed on the top of a thin-walled brass cylinder (the "plunger"), 10 cm. high, open below, and sliding freely within an outer brass cylinder (the "expansion cylinder") of the same height and about 16 cm. in internal diameter. The expansion cylinder supports the walls of the cloud chamber and rests on a thin sheet of indiarubber lying on a thick brass disc, which forms the bottom of a shallow receptacle containing water to a depth of about 2 cm. The

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water separates completely the air in the cloud chamber from that below the plunger. The base plate rests on a wooden stand, not shown on the diagram.

The expansion is effected by opening the valve B and so putting the air space below the plunger in communication with the vacuum chamber C

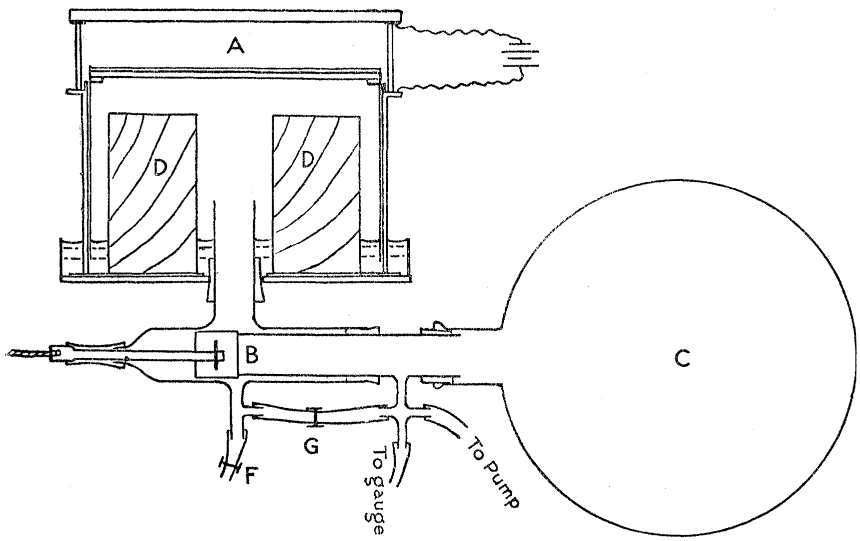

Fig. 1.

through wide glass connecting tubes of about 2 cm. in diameter. The floor of the cloud chamber, in consequence, drops suddenly until brought to a sudden stop, when the plunger strikes the indiarubber-covered base plate, against which it remains firmly fixed by the pressure of the air in the cloud chamber. To reduce the volume of air passing through the connecting tubes at each expansion the wooden cylinder D was inserted within the air space below the plunger.

The valve is opened by the fall of a weight W released by a trigger arrangement T (fig. 3). On closing the valve and opening communication with the atmosphere through the pinch-cock F, the plunger rises and so reduces the volume of the air in the cloud chamber. By means of the two pinch-cocks F and G (the latter on a tube communicating with the vacuum chamber), the plunger may be adjusted to give any desired initial volume v_1 between the upper limit v_2—the maximum volume of the cloud chamber—and the lower limit reached when the pressure below the plunger is that of the atmosphere.

The final volume v_2 is always the same (about 750 c.c.), the expansion ratio v_2/v_1 depending only on the initial volume. A scale attached to the side of the cloud chamber enables the position of the top of the plunger to be read, and hence the initial volume to be determined, the area of the cross-section of the plunger and the maximum volume v_2 of the cloud chamber being known.

In setting up the apparatus, the plunger is placed on the rubber-covered base plate, and the expansion cylinder slipped over it, a hole in the side of the cloud chamber being open at this stage to allow of the imprisoned air escaping. Then, by blowing in air through F, momentarily opened for the purpose, the plunger is driven up to a height sufficient to allow of the largest desired expansions being made. The aperture in the wall of the cloud chamber is then closed, and the mass of imprisoned air remains unchanged during subsequent operations.

The gelatine layer under the roof of the cloud chamber is connected, through a ring of tinfoil cemented between the cylindrical wall and the roof, with one terminal of a battery of cells of which the other terminal is connected, through the brass expansion cylinder and plunger, with the layer of blackened gelatine on the floor of the cloud chamber. An approximately uniform vertical electric field of any desired intensity may thus be maintained in the cloud chamber.

The gelatine lining of the roof and walls is formed by pouring into the cloud chamber, before attaching it to the expansion cylinder, a hot solution containing about 4 per cent. of gelatine and 0·1 per cent. of boracic acid and allowing the surplus to drain away by inverting the vessel. The thin coating of gelatine which remains is allowed to dry over calcium chloride. The cloud chamber is cemented to the expansion cylinder by means of gelatine.

A comparatively thick layer (about 1 mm.) of a solution containing 15 per cent. of gelatine, 2 per cent. of boracic acid, and 3 per cent. of Indian ink is poured on to the glass plate which forms the floor of the cloud chamber, the brass walls of the plunger being prolonged for about 1 mm. above the upper surface of the plate, thus forming a shallow receptacle for the gelatine and making an efficient electric contact with it. The blackened gelatine is not allowed to dry, but at once covered to prevent evaporation and to protect it from dust till ready for use. The gelatine is in all cases previously sterilised by heat.

Method of Illuminating and Photographing the Clouds.

As in the experiments described in my last paper, a Leyden jar discharge through mercury vapour at atmospheric pressure is used for the instantaneous illumination of the clouds resulting from the expansion. A horizontal silica tube (fig. 2) about 15 cm. long, and having an internal diameter of about 1 mm., is filled with mercury and enclosed, for the central 4 cm. of its length, by a close-fitting silver tube about 2 mm. thick, and having a slot about 1 mm. wide extending from end to end. The silver tube when heated by a small flame serves to keep the enclosed portion of the silica tube at a nearly uniform temperature high enough to vaporise the mercury, and thus

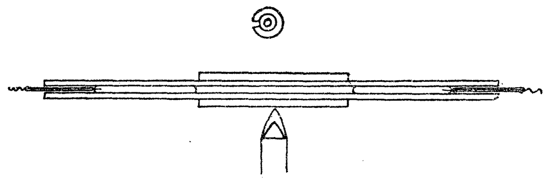

FIG. 2.

form a mercury-vapour spark-gap. Connection with the Leyden jars is made through platinum wires fused through the ends of glass tubes filled with mercury and inserted into the ends of the silica tube.

The silica tube is first filled with mercury, the end pieces inserted, and a small flame placed under the silver tube. When the mercury occupying the portion of the silica tube which is surrounded by the silver jacket has all been vaporised (the excess of mercury escaping from the ends of the tube) no further change takes place and the spark-gap is ready for use. The very considerable capillary forces set up when the mercury is forced into the narrow space between the glass end pieces and the surrounding silica tube effectually prevent the violent oscillatory motions which are apt to be the principal source of trouble in the use of a mercury spark-gap of this type.

For firing the spark the arrangement used is essentially that which has generally been employed in instantaneous photography by the Leyden jar discharge. The outer coatings of two sets of 4 or 5 "gallon" Leyden jars, standing on the floor of the room, are connected to the terminals of the illuminating spark. The inner coatings are connected to the terminals of a Wimshurst machine and to two brass balls separated by a space of about 5 cm. which forms the primary spark-gap. The jars having been charged almost to sparking potential, a metal ball is allowed to fall between the terminals of the primary spark-gap, causing a spark to pass at both gaps. The ball whose fall causes the spark is hung by a fine thread, just strong enough to carry it, from the weight W which works the valve of the expansion apparatus.

The arrangements for firing the spark at a definite interval after the expansion are shown diagrammatically in fig. 3. The weight W is carried by a cord which passes through an iron ring in a firm support, and thence nearly horizontally to the trigger T, to which it is attached by a loop. A second string, slack at this stage, connects a point on the first cord with the valve of the expansion apparatus. On pulling the trigger the cord attached to it is released and the weight falls until the second string is stretched tight, when it is brought to a sudden stop, the valve being simultaneously opened and the expansion thereby effected. The thread breaks at this moment and the steel

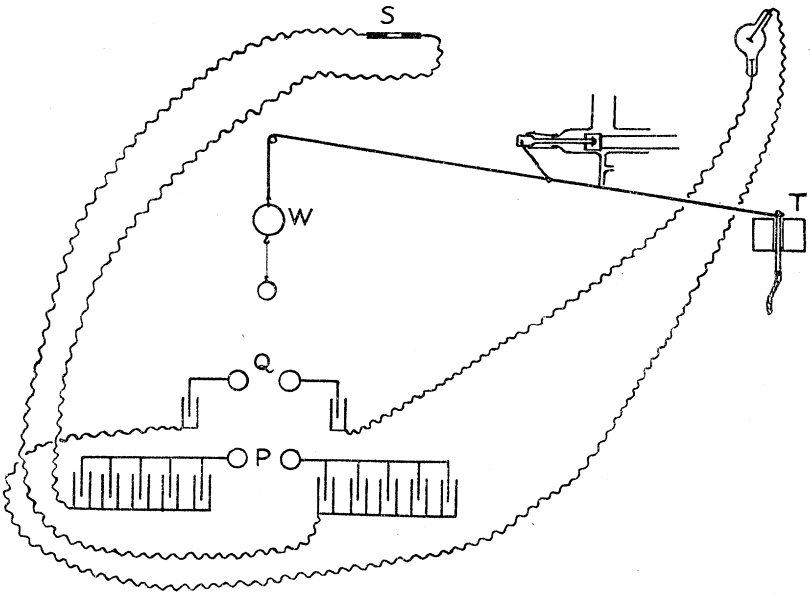

Fig. 3.

sphere continues to fall, finally passing through the primary spark-gap, P, and causing the illuminating spark to pass at S. The upper spark-gap, Q, shown in the figure, was only employed in the experiments with X-rays.

In the experiments described in this paper, the camera lens has always occupied one of the two positions indicated diagrammatically in fig. 4, (a) and (b). In (a) the small circle represents a transverse section of a narrow

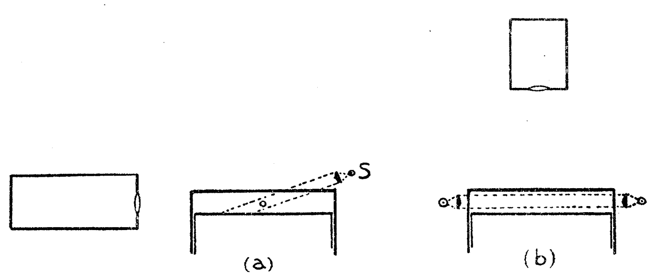

Fig. 4.

horizontal beam of ionising rays crossing a diameter of the cloud chamber. The camera looks in a horizontal direction normal to the ionising beam. The mercury spark-gap is at S, at the principal focus of a cylindrical lens about

20 cm. long and 2 cm. wide, and having a focal length of about 3 cm. With this arrangement the whole of the cloud produced by a considerable length of the ionising beam is illuminated, while the direction of the incident light makes a comparatively small angle (about 25°) with the axis of the camera.

Arrangement (b) has been used chiefly with the α-rays, which give clouds of sufficient density to scatter a large amount of light at right angles to the illuminating beam. The camera lens is vertically over the centre of the cloud chamber; and by means of two similar mercury spark-gaps (arranged in series), each at the principal focus of a cylindrical lens like that used in (a), a horizontal stratum of about 2 cm. in vertical thickness and extending across the whole area of the vessel, is illuminated.

The lens which I have used is a Beck "isostigmar," the full aperture, marked F 5·8, being utilised; Ilford "Monarch" plates were employed.

Ionisation by α-Rays. (Plate 6, and fig. 1 of Plate 7.)

Fig. 1 (Plate 6) is a typical photograph of the cloud obtained on expansion when a minute quantity of radium is placed on the tip of a wire projecting into the cloud chamber. A potential difference of 40 volts was maintained between the roof and floor, the roof being at the higher potential. The camera was placed with its axis vertical, and a horizontal section of the cloud chamber, about 2 cm. in depth, was illuminated (arrangement (b) of fig. 4). The β-rays are not visible in the photographs obtained with this mode of illumination.

The narrow, sharply defined rays of these photographs are clouds condensed along the tracks of α-particles which have traversed the supersaturated air after the expansion, so that there has been very little time for the ions to diffuse before losing their mobility through condensation of water upon them. The diffuse rays are clouds condensed upon ions set free by α-particles which have traversed the air before its expansion, so that there has been time for diffusion of the ions before the formation of the cloud. The weaker the electric field the greater is the maximum possible age, and consequent diffuseness, of the tracks which may be present; with a potential difference of only two or three volts, wide finger-like clouds are formed on expansion.

α-rays which pass after the expansion can only leave visible trails if the degree of supersaturation still remains sufficient to cause water to condense on the ions. In the immediate neighbourhood of the cloud already condensed on an older track, the supersaturation remaining may be insufficient to cause condensation, although elsewhere the α-particle may leave a visible trail. This is doubtless the explanation of the fact that most of the sharply defined trails only seem to begin at some considerable distance from the radium, the diffuse cloud trails formed at the moment of expansion being so closely packed near the source of the rays that there is little chance of an α-particle, ejected after the expansion, finding the supersaturation necessary for rendering its trail visible, until it has travelled for some distance.

Except in the case of photographs taken very soon after the insertion of the radium, the trails of α-particles from the emanation and later radioactive products also appear. Fig. 4 is a photograph of the cloud formed by expansion after the radium-tipped wire had been for some days in the cloud chamber and had then been removed; α-rays are seen running in all directions. A sharply defined trail may sometimes be observed crossing one or more diffuse ones, and is then frequently invisible for some little distance on either side of the diffuse ray, the necessary supersaturation not being attained owing to previous condensation on the ions of the older trail.

For some purposes (if, for example, the ranges of the α-particles were under investigation) it would be necessary to know definitely whether the α-particle giving rise to any given trail had passed before or after the expansion, the density of the air traversed being different in the two cases. The trails of α-particles passing previously to the expansion have their dimensions altered between the liberation of the ions and the deposition of water upon them; but, the displacement of the air being everywhere nearly in a vertical direction, the horizontal dimensions are almost unaffected. In the photographs it will be observed that the diffuse rays are shorter than the sharply defined rays in accordance with the greater density of the air at the moment of passage of the α-particle.

There is no difficulty in securing that the particles whose tracks are being photographed shall have passed either all before or all after the expansion. It is only necessary to attach to the plunger a vertical plate (glass 2 mm. thick was used) immediately in front of the source of the rays, and with a horizontal slot so placed that it shall be at the level of the radiant point either before or after the expansion. Fig. 2 is a photograph taken under the latter condition; the diffuse tracks are now absent. This method is, of course, inapplicable to the study of the rays from the emanation within the cloud chamber.

As will be seen from the photographs, the α-rays are generally straight over the greater part of their length, but they nearly all are bent, often abruptly, in the last 2 mm. of their course. Abrupt bends through considerable angles are seen much earlier in the course of some of the rays.

In fig. 3 of Plate 6 is shown an enlargement of a particularly interesting trail. Here there are two absolutely abrupt bends—the first through about $10\frac{1}{2}°$, the second through about 43°. There is a very well-marked spur at the second bend, which it is difficult to interpret otherwise than as being due to ionisation by the recoil of the atom, by collision with which the course of the α-particle has been abruptly changed. (But for the spur this α-ray shows an astonishingly close resemblance to one in a diagram constructed by Prof. Bragg* to illustrate what he considered to be likely forms of α-ray paths.)

Apart from these sudden bends a certain amount of curvature is apparent in some of the tracks. In some cases, where the curvature occurs close to the walls of the cloud chamber, it is certainly a spurious effect, due to displacement of the tracks by air motions or to optical distortion arising from a thickening of the gelatine round the circumference of the roof. Where, however, it appears at no great distance from the centre of the cloud chamber it is probably genuine, indicating deviation of the α-particle by repeated small deflections. There is generally unmistakably genuine curvature in the last millimetre of the track.

The photographs thus furnish evidence of two distinct ways in which α-particles are "scattered" in passing through air, what Rutherford† has called "single" and "compound" scattering respectively. And, as Rutherford has contended, the scattering of large amount is in the case of α-particles mainly due to the former process, that is to say, it is the result of single deflections through considerable angles and not a cumulative effect due to a very large number of minute deviations.

When the α-rays arise from the emanation it is possible to photograph the complete track of an α-particle, including the beginning and end. The latter is at once recognisable by its characteristic bend or hook. In figs. 4 and 5 (Plate 6) are shown the tracks of two α-particles, each of which has completed its course in the illuminated layer; in both cases the beginning of the trail is seen to be marked by an enlarged head in which the cloud is of greater density than elsewhere. This may represent ionisation by the recoil of the atom from which the α-particle has escaped. The same characteristic head appears at what is presumably the beginning of other, obviously foreshortened, tracks whose ends lie outside the illuminated layer.

Of the two complete α-ray tracks from the emanation one has a length (when reduced to 760 mm. and 15° C.) of 4·3 cm., in good agreement with the usually accepted value of the range. The other is apparently somewhat shorter, about 3·8 cm., the low value being probably due to foreshortening.

* 'Archives of the Röntgen Ray,' April, 1911.

† 'Phil. Mag.,' 1911, vol. 21, p. 669.

Some photographs of α-ray trails were obtained with the camera in the lateral position and with oblique illumination—arrangement (a) of fig. 4 (p. 281). The radium tipped wire was surrounded by a glass tube about 1 mm. wide open at the end and projecting for about 1 cm. beyond the radium, the object being to confine the rays to a moderately narrow pencil with its axis in the plane for which the camera was focussed.

An example of one of the photographs obtained in this way is shown in Plate 7, fig. 1, which is an enlargement of the original negative. The track of an α-particle is seen near the bottom of the picture. Some of the ions appear to have retained their mobility in the supersaturated atmosphere long enough to enable them to travel some distance under the action of the electric field before growing into drops, thus giving rise to a vertical sheet or curtain of drops. The effect is most marked above the main track, *i.e.* on the side to which the negative ions would travel.

I have not yet succeeded in obtaining photographs in which all the drops in a known length of the cloud trail left by an α-particle could be counted. It would obviously be of interest to determine by a direct method of this kind the number of ions produced by an α-particle.

Ionisation by β-Rays. (Plate 7.)

When the camera is in the lateral position and oblique illumination is used the individual cloud particles, so long as they are not too close together for resolution, leave distinct images on the photographic plate. It is possible, therefore, to photograph the track of any ionising particle, however small the number of ions produced per centimetre of its path may be.

Some photographs of β-ray trails were obtained along with those of the α-rays in the course of the experiments last described. Figs. 1, 3, and 4 of Plate 7 were obtained in this way; fig. 2 shows the result of passing a narrow beam of γ-rays through the cloud chamber; the tracks in this case are doubtless those of β-particles starting in the walls of the vessel.

The almost straight trail of figs. 3 and 4 (the actual length of trail photographed amounts to about 4 cm.) is evidently that of a β-particle in the earlier stage of its free existence while its velocity is still very high. This is indicated not only by the straightness of its path but also by the very small ionisation along it. The distribution of the ionisation along the path is interesting. Over considerable distances the ions occur mainly in pairs, but here and there 20 or 30 appear to have been liberated in a closely packed group. (A similar distribution appears in a second approximately straight ray which crosses the first.) The groups show a peculiarity which is also met with in the clouds condensed on the cathode rays produced by X-rays when a suitable expansion ratio is used: while the negative ions have given rise to a densely packed cluster of drops the positive ions have been drawn out by the electric field before losing their mobility, giving the appearance of a shower of drops falling from the negative cloud.

If we omit the clusters, the number of ions in the trail amounts to about 32, *i.e.* 16 pairs, per centimetre at atmospheric pressure. If we take into account the groups the number of ions per centimetre is roughly doubled, giving a number not very much lower than the estimate of 48 pairs per centimetre obtained by Eve* by indirect methods.

The occurrence of the groups or clusters of ions may be interpreted as indicating that in certain cases the corpuscle liberated from an atom by a β-particle of high velocity may itself have energy enough to ionise for a very short distance. The β-rays of fig. 2 are obviously of smaller velocity, producing much more ionisation per centimetre and being much more readily deviated.

A still later stage of slower velocity has been reached by the particles giving the abruptly ending coiled up trails which appear in figs. 1 and 3. These β-ray endings are indistinguishable from the cathode rays, produced in air by Röntgen rays, such as are shown in the succeeding plates.

It will be noticed that the β-rays photographed do not show abrupt deflections like the α-rays, but, except while the velocity remains very high, they show gradual bending resulting in large deviations. The scattering of the β-rays is thus mainly or entirely of the cumulative or "compound" type, being due to a large number of successive deflections, each in itself inappreciable.

Ionisation by Röntgen Rays. (Plates 8 and 9.)

The X-ray bulb was excited by a Leyden jar discharge, in most cases so timed that the rays traversed the cloud chamber immediately after the expansion, while the gas was in the supersaturated condition. The ions had thus extremely little time in which to diffuse before being fixed by the condensation of water upon them.

The terminals of the upper spark gap Q of fig. 3 (p. 281) were connected with the inner coatings of two Leyden jars, the outer coatings of which were connected to the Crookes tube. The inner coatings were also connected through glass tubes filled with water to the terminals of the Wimshurst machine. The steel ball in its fall first caused the X-ray discharge and afterwards the illuminating spark, the water tubes having a sufficiently high resistance to prevent the jars supplying the illuminating spark from discharging while the ball traversed the upper spark gap, but conducting sufficiently well

* 'Phil. Mag.,' 1911, vol. 22, p. 551.

to allow of both sets of jars being simultaneously charged by means of the Wimshurst machine.

The moment of occurrence of the X-ray flash relative to the expansion was adjusted by varying the length of the thread suspending the steel ball. Tests were made of the length of thread required to make the X-ray discharge simultaneous with the completion of the expansion; it was then known that with a thread shorter than this the X-rays would pass after the expansion. For the purpose of making this test the X-ray tube was removed, and the wires supplying it were connected instead to the mercury spark-gap; two illuminating sparks thus traversed the mercury vapour during the fall of the ball, the interval between them being the same as that between the X-ray flash and the illuminating spark, for the same length of thread, in the ordinary use of the apparatus. A series of photographs was taken with different lengths of thread, the camera, placed horizontally, being focussed on a pointer attached to the plunger; a single image of the pointer on the photographic plate indicated that the expansion had been completed before the passage of the first spark, a double image resulting if the first spark passed before the expansion was completed. These photographs also furnished information regarding the rapidity of the expansion; it was found to be completed within about 1/50th of a second.

The Crookes tube was fixed at a distance varying from 30 to 70 cm. from an aperture in the wall of the cloud chamber about 1·2 cm. in diameter; this was closed by a quartz plate 0·38 mm. thick. The quartz window was used as it happened to be convenient for another purpose. The rays passed through a narrow cylindrical channel, in most cases of 2 mm. bore, in a lead block about 5 cm. thick placed close to the quartz window, lead screens being also inserted to shield the rest of the cloud chamber from the rays. The camera occupied position (a) of fig. 4. A horizontal cylindrical beam of X-rays was in this way made to traverse the cloud chamber across its centre, and was at such a distance from the camera that the magnification was about 2·45 diameters. To avoid distortion by the cylindrical walls of the cloud chamber a portion of the cylinder 5 cm. in length was removed and replaced by a plane parallel glass plate.

Photographs of some typical X-ray clouds are shown in Plate 8. In all cases (with one exception, fig. 5) the rays traversed the supersaturated gas, the order of events being: (1) Production of the supersaturated condition by sudden expansion; (2) Leyden jar discharge through the Crookes tube, causing ionisation within the cloud chamber; (3) condensation of water upon the ions; (4) passage of the illuminating spark, giving a photograph of the cloud condensed on the ions.

The potential difference between the top and bottom of the cloud chamber was in some cases 40 volts, in others only 4 volts, the top being always positive.

In most cases the expansion ratio was between 1·33 and 1·36; *i.e.* it considerably exceeded the minimum (approximately 1·31) required to cause condensation on the positive as well as the negative ions (the minimum for the latter is 1·25), but less than is required to give dense clouds in the absence of ions ($v_2/v_1 = 1{\cdot}38$). Under these conditions, as the photographs show, the tracks of the cathode- or β-particles produced in the gas by the X-rays are very sharply defined, the ions being fixed by condensation of water upon them before they have had time to diffuse, or travel under the action of the electric force, for any appreciable distance.

The following are among the more striking features of the photographs, of which figs. 1 to 4 of Plate 8 are a few examples out of a considerable number obtained under these conditions.

1. Cathode or β-rays are seen to start from within the track of the primary X-ray beam, many of them extending to some distance outside it.

2. There is no indication of any effect of the X-rays on the gas other than the production of the corpuscular radiation; the track of the primary X-ray beam is not distinguishable otherwise than as being the region in which the β-rays have their origin. In some photographs, it is true, there appear scattered throughout the region illuminated by the spark drops which might be taken to represent ions set free by the X-rays, but these show no concentration along the path of the primary beam, and, moreover, they appear in equal numbers in comparison photographs taken under conditions otherwise identical but without any X-ray discharge. There is no doubt, I think, that these scattered drops are condensed upon uncharged nuclei similar in nature to those produced by weak ultra-violet light and certain metals, which require a similar expansion to catch them. They appear to be due to a chemical action in which some trace of impurity plays an essential part, as they are much more numerous when the air in the apparatus has recently been renewed.

Ionisation by X-rays appears therefore to be, as Bragg has suggested, entirely a secondary process, except in so far as each cathode ray produced in the gas may be said to indicate the formation of one pair of ions by the X-radiation.

3. The number of cathode rays produced in air in a known length of a limited beam of X-rays can readily be counted by this method.

4. The X-radiation thus far used has been heterogeneous. It is to be expected therefore that the cathode rays should be of varying length. Reduced to atmospheric pressure, a frequent length, measured along the

path, was from $\frac{3}{4}$ to 1 cm., or measured in a straight line from beginning to end of the path, about half these amounts. Tracks as long as 2 cm. were, however, met with.

5. The rays show two distinct kinds of deflection as a result of their encounters with the atoms of the gas—Rutherford's "single" and "compound" scattering. The gradual or cumulative deviation due to successive deflections of very small amount is evidently, however, in this case much the more important factor in causing scattering, all the rays showing a large amount of curvature, while quite a small proportion show abrupt bends. When abrupt deflections occur they are frequently through large angles, 90° or more.

6. The rays tend to become more and more bent as the end is approached, the actual end of each cloud trail being also enlarged into a kind of head, possibly owing to the path of the corpuscle finally becoming extremely irregular in form.

7. In many of the photographs there are cloud trails sufficiently sharply in focus over at least a portion of their length to show the individual drops and, therefore, allow of the ions on which they have condensed being counted. An enlargement of one such track is shown in fig. 6 of Plate 8; the number per cm. of this trail amounts to about 278, the equivalent of 376 ions or 188 pairs of ions at atmospheric pressure. This number appears to be fairly typical for the middle portions of the tracks, *i.e.* about 5 mm. from the end. Out of 12 counts of this kind, the smallest number obtained is 150 pairs per cm. (at atmospheric pressure)—this is at the beginning of a ray—the largest 2160 pairs per cm. in the last $\frac{1}{2}$ mm. of a ray.

8. The cathode rays appear to start in all directions. I have not yet attempted any systematic statistical study such as would be required to determine the relative frequency of different initial directions of the rays with respect to the direction of propagation of the Röntgen radiation.

When the expansion ratio is less than about 1·33, the cathode-ray cloud-trails begin to lose their sharpness, as is illustrated by the photographs in Plate 9. With expansion ratios between 1·31 and 1·33, the positive ions are spread out by the electric field before becoming fixed, giving rise to what looks like a shower of drops falling from each trail, which is still marked by the negative ions. When the expansion falls below that required to catch the positive ions, the negative ions begin to show a similar spreading out under the action of the field, and finally, while the expansion still considerably exceeds that required to catch negative ions, the clouds cease to give any picture of the original path of the corpuscle. To get the form of the path of an ionising particle as accurately as possible, the expansion ratio ought to exceed 1·33; but, on the other hand, for counting the ions, a smaller expansion has advantages. An expansion just too small to catch positive ions is perhaps the best for counting the ions; it was only in photographs obtained under such conditions that the ionisation at the ends of the trails could be determined.

When the Röntgen rays are flashed through the cloud chamber before the expansion of the air, diffuse double tracks are obtained, the positive and negative ions being separated by the electric field, and a certain amount of diffusion of the ions occurring in both positive and negative trails (Plate 8, fig. 5). It would have been interesting to obtain by this very direct method a test as to whether the number of positive and negative ions set free is the same, or, in other words, whether the positive and negative ion carry equal charges—a question which has been raised by certain experiments by Townsend. Unfortunately, I have thus far only succeeded in obtaining on the negatives a few very short portions of such double tracks, which are at the same time sharply in focus and free from complications due to overlapping with other tracks. These short portions do, however, show equality in the numbers of positive and negative ions; the positive and negative clouds, to take one example, containing each 30 to 31 drops, there being some uncertainty in one or two cases as to whether an image on the plate represents one drop or two.

These experiments have been carried out in the Cavendish Laboratory. I have to thank Mr. F. Lincoln and his assistants in the workshop for most efficient aid in the construction of the apparatus.

DESCRIPTION OF THE PLATES.

The pictures are photographs of clouds condensed on the ions set free in moist air by rays of different kinds. In what follows, ρ_1 is the density of the air before expansion (relative to saturated air at 15° C. and 760 mm.), ρ_2 the density after expansion, v_2/v_1 the expansion ratio, V the potential difference between the roof and floor of the cloud chamber, and M the magnification. In all cases the roof of the cloud chamber was positive, so that positive ions travelled downwards, negative upwards.

Plate 6.

Ionisation by α-rays.

Axis of camera vertical ; horizontal layer of 2 cm. in depth illuminated by mercury spark.

Fig. 1. α-Rays from radium. Some of the α-particles have traversed the air before the expansion, others after the expansion.

$\rho_1 = 0{\cdot}98$, $v_2/v_1 = 1{\cdot}36$, $\rho_2 = 0{\cdot}72$, V = 40 volts, M = 1/2·18.

Fig. 2. α-Rays from radium. The α-particles have all traversed the air after the expansion.

$\rho_1 = 0{\cdot}97$, $v_2/v_1 = 1{\cdot}33$, $\rho_2 = 0{\cdot}73$, V = 40 volts, M = 1·05.

Fig. 3. α-Rays from radium. Enlargement of a portion of fig. 2.

$\rho_1 = 0{\cdot}97$, $v_2/v_1 = 1{\cdot}33$, $\rho_2 = 0{\cdot}73$, V = 40 volts, M = 2·57.

Fig. 4. α-Rays from radium emanation and active deposit.

$\rho_1 = 1{\cdot}00$, $v_2/v_1 = 1{\cdot}36$, $\rho_2 = 0{\cdot}74$, V = 40 volts, M = 1/1·24.

Fig. 5. A complete α-ray from radium emanation.

$\rho_1 = 0{\cdot}97$, $v_2/v_1 = 1{\cdot}36$, $\rho_2 = 0{\cdot}71$, V = 40 volts, M = 1·16.

Plate 7.

Ionisation by α- and β-rays. The source of the rays is on the right of the picture.

Axis of camera horizontal (arrangement (a) of p. 281).

Fig. 1. α- and β-Rays from radium.

$\rho_1 = 0{\cdot}98$, $v_2/v_1 = 1{\cdot}33$, $\rho_2 = 0{\cdot}74$, V = 30 volts, M = 6·0.

Fig. 2. β-Rays produced by γ-radiation.

$\rho_1 = 1{\cdot}00$, $v_2/v_1 = 1{\cdot}34$, $\rho_2 = 0{\cdot}75$, V = 40 volts, M = 6·0.

Fig. 3. β-Rays from radium.

$\rho_1 = 0{\cdot}99$, $v_2/v_1 = 1{\cdot}31$, $\rho_2 = 0{\cdot}76$, V = 40 volts, M = 2·45.

Fig. 4. β-Rays. Enlargement of a portion of fig. 3.

$\rho_1 = 0{\cdot}99$, $v_2/v_1 = 1{\cdot}31$, $\rho_2 = 0{\cdot}76$, V = 40 volts, M = 6·0.

PLATE 8.

Ionisation by Röntgen rays.

Axis of camera horizontal, X-rays passing from right to left.

In all cases except fig. 5 the X-rays traversed the air after the expansion.

Fig. 1. Ionisation by cylindrical X-ray beam about 2 mm. in diameter.

$\rho_1 = 1{\cdot}00$, $v_2/v_1 = 1{\cdot}35$, $\rho_2 = 0{\cdot}74$, V = 4 volts, M = 2·45.

Fig. 2.* Ionisation by X-ray beam about 2 mm. in diameter.

$\rho_1 = 1{\cdot}00$, $v_2/v_1 = 1{\cdot}34$, $\rho_2 = 0{\cdot}75$, V = 4 volts, M = 2·45.

Fig. 3. Ionisation by X-ray beam about 2 mm. in diameter.

$\rho_1 = 0{\cdot}93$, $v_2/v_1 = 1{\cdot}33$, $\rho_2 = 0{\cdot}70$, V = 40 volts, M = 2·45.

Fig. 4. Ionisation by X-ray beam about 5 mm. in diameter.

$\rho_1 = 1{\cdot}00$, $v_2/v_1 = 1{\cdot}36$, $\rho_2 = 0{\cdot}74$, V = 40 volts, M = 2·45.

Fig. 5. Ionisation by X-ray beam about 5 mm. in diameter. The X-rays traversed the air before its expansion; the positive and negative ions have been separated by the electric field before losing their mobility by the condensation of water upon them.

$\rho_1 = 1{\cdot}00$, $v_2/v_1 = 1{\cdot}36$, $\rho_2 = 0{\cdot}74$, V = 40 volts, M = 2·45.

Fig. 6. Portion of fig. 4 enlarged, showing the individual ions produced along a portion of one of the cathode-ray tracks. (The fig. has been turned through 90°.)

$\rho_1 = 1{\cdot}00$, $v_2/v_1 = 1{\cdot}36$, $\rho_2 = 0{\cdot}74$, V = 40 volts, M = 14·7.

PLATE 9.

Ionisation by Röntgen rays. Conditions as in Plate 8; X-ray beam about 2 mm. in diameter. Figs. 2, 3, and 4 belong to a series in which the expansion ratio v_2/v_1 was varied while all other conditions were kept constant.

Fig. 1. Enlargement of a portion of fig. 1, Plate 8.

$\rho_1 = 1{\cdot}00$, $v_2/v_1 = 1{\cdot}35$, $\rho_2 = 0{\cdot}74$, V = 4 volts, M = 6·0.

Fig. 2. Enlargement of portion of fig. 3, Plate 8. In this, as in all the preceding X-ray pictures, the maximum supersaturation attained has been sufficient to cause the ions to lose their mobility immediately after being set free so that the cathode-ray particles leave sharply defined trails.

$\rho_1 = 0{\cdot}93$, $v_2/v_1 = 1{\cdot}33$, $\rho_2 = 0{\cdot}70$, V = 40 volts, M = 6·0.

Fig. 3. The maximum supersaturation has only slightly exceeded that required to cause condensation on the positive ions, which have therefore travelled varying distances under the action of the electric field before becoming fixed by condensation of water.

$\rho_1 = 0{\cdot}92$, $v_2/v_1 = 1{\cdot}31$, $\rho_2 = 0{\cdot}70$, V = 40 volts, M = 6·0.

Fig. 4. Negative ions, which alone are caught with the maximum degree of supersaturation attained, have retained their mobility for varying lengths of time, the cathode-ray trails being therefore drawn out into diffuse sheets under the action of the electric field.

$\rho_1 = 0{\cdot}90$, $v_2/v_1 = 1{\cdot}28$, $\rho_2 = 0{\cdot}70$, V = 40 volts, M = 6·0.

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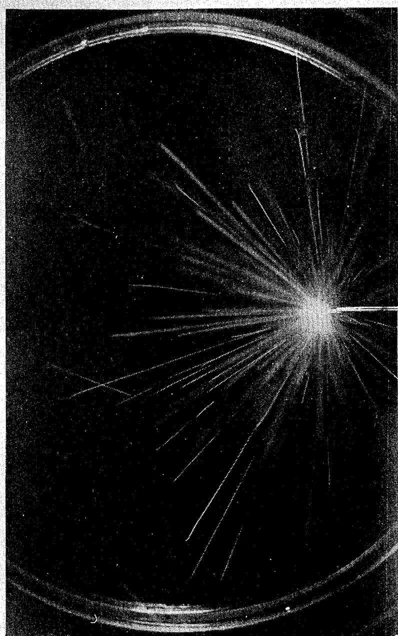
* Fig. 2 of Plate 8 has by accident been placed upside down.



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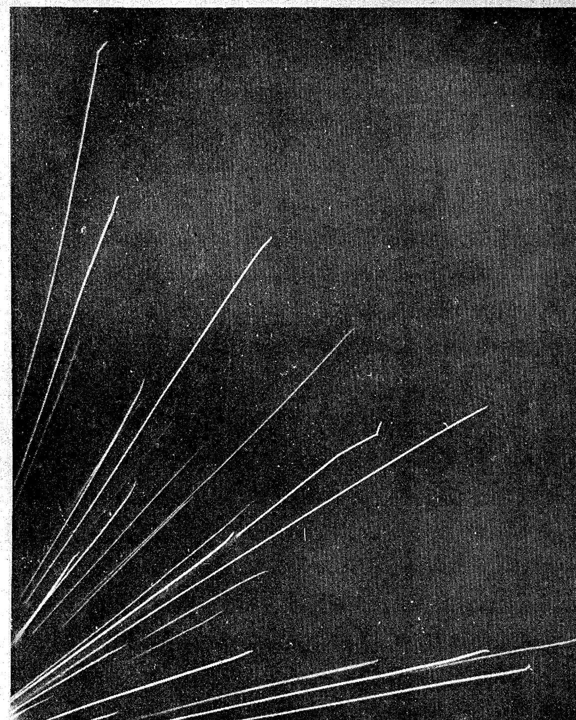

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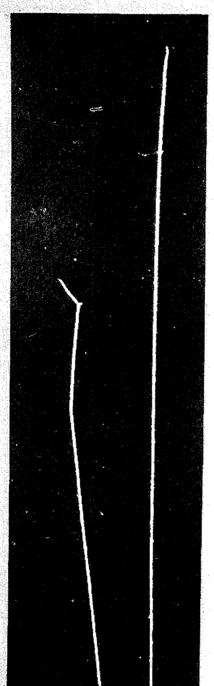

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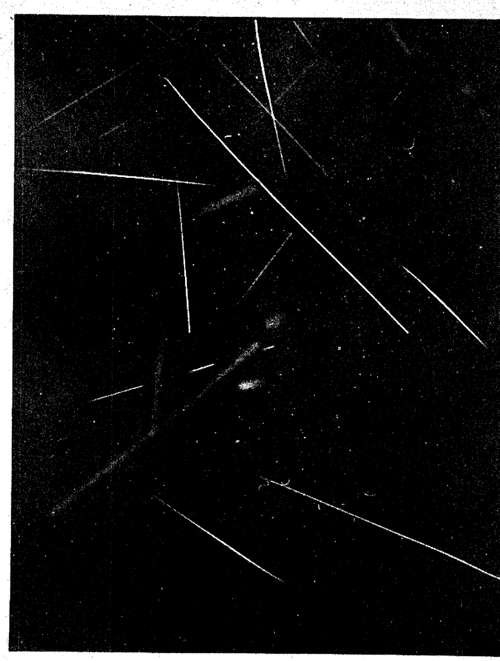

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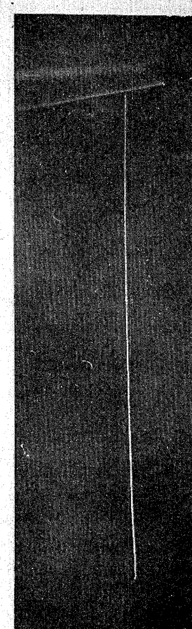

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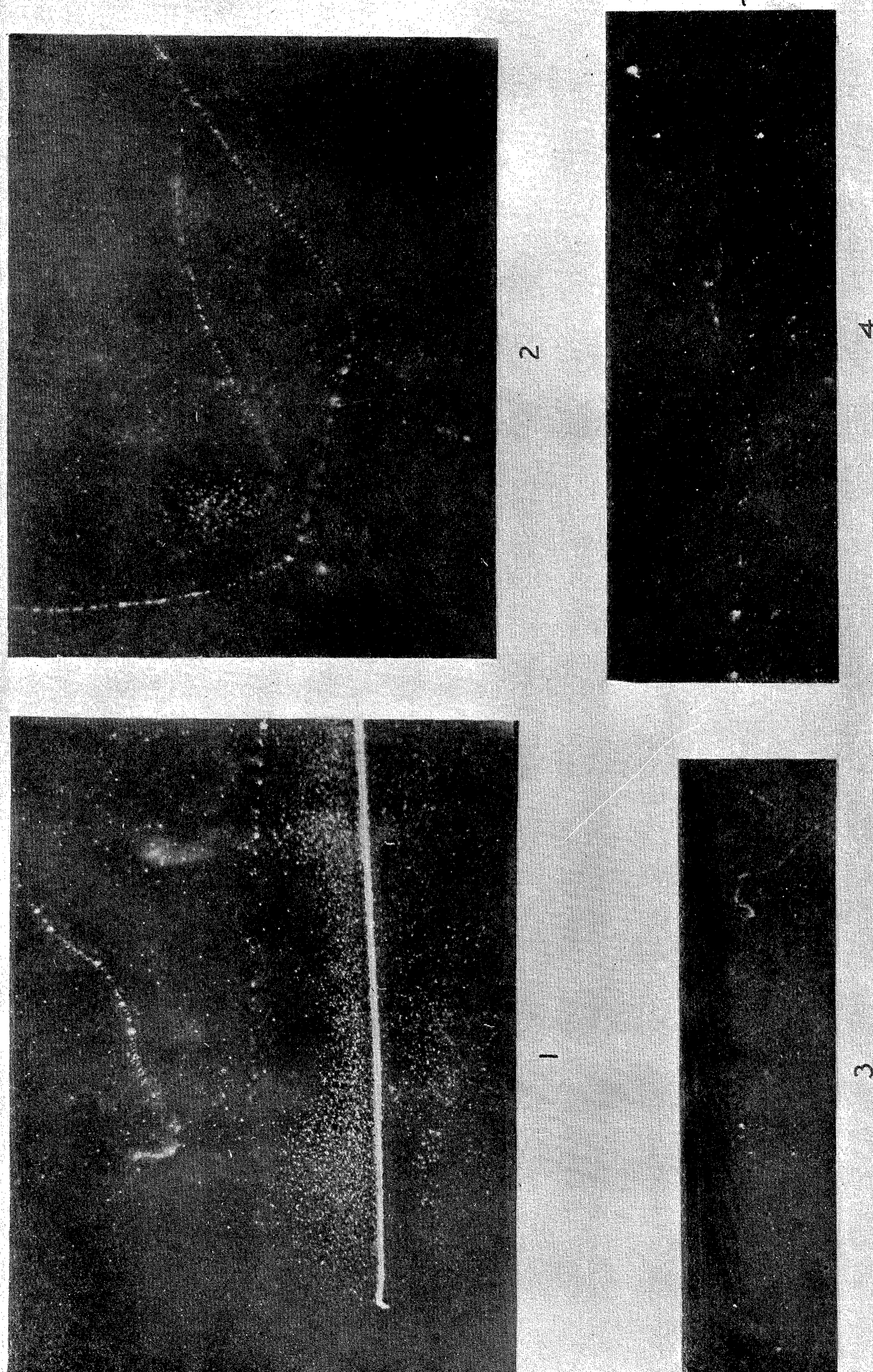
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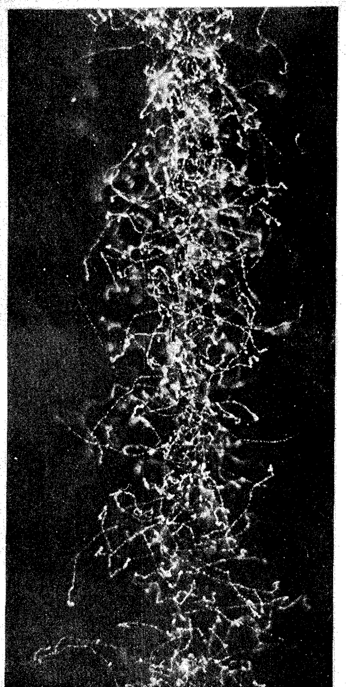

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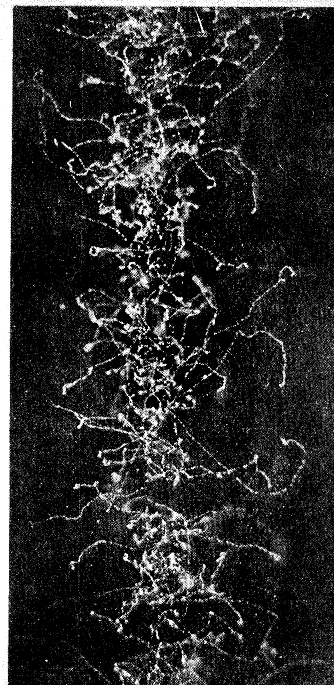

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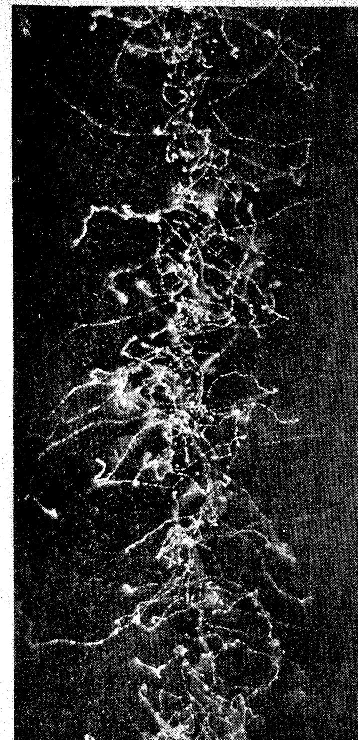

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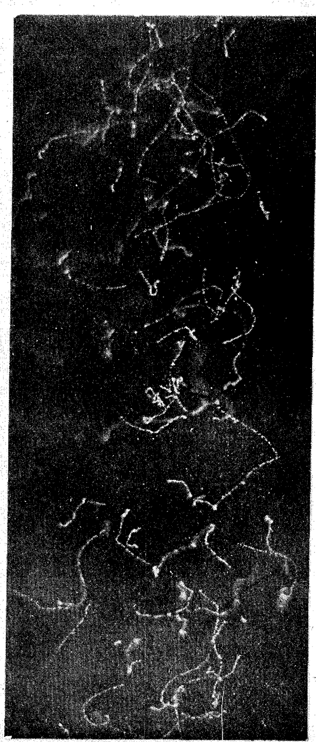

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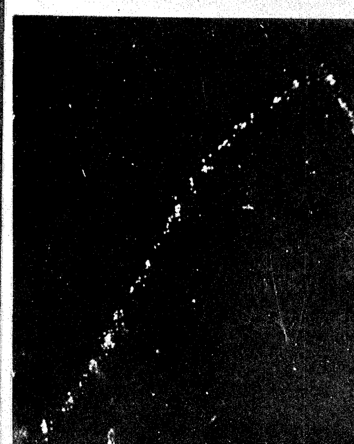

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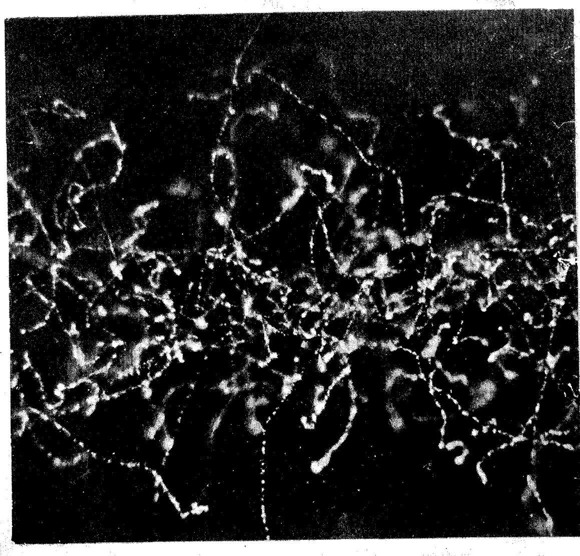

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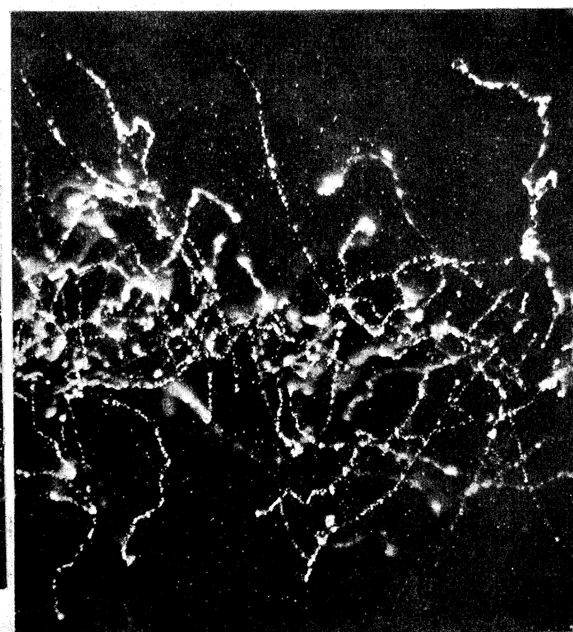

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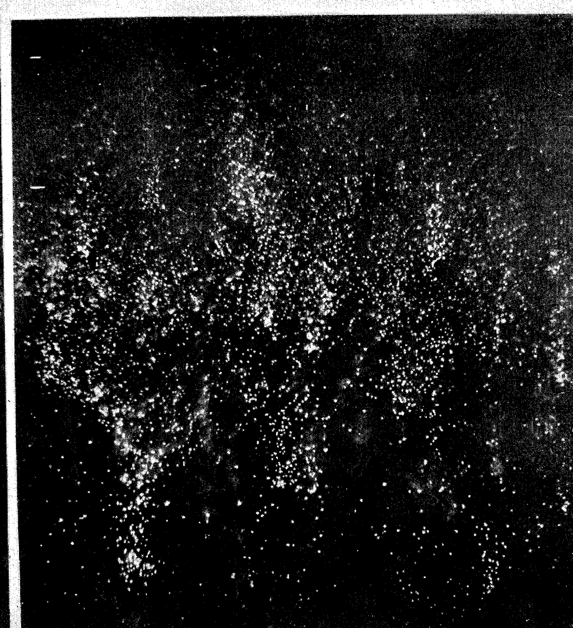

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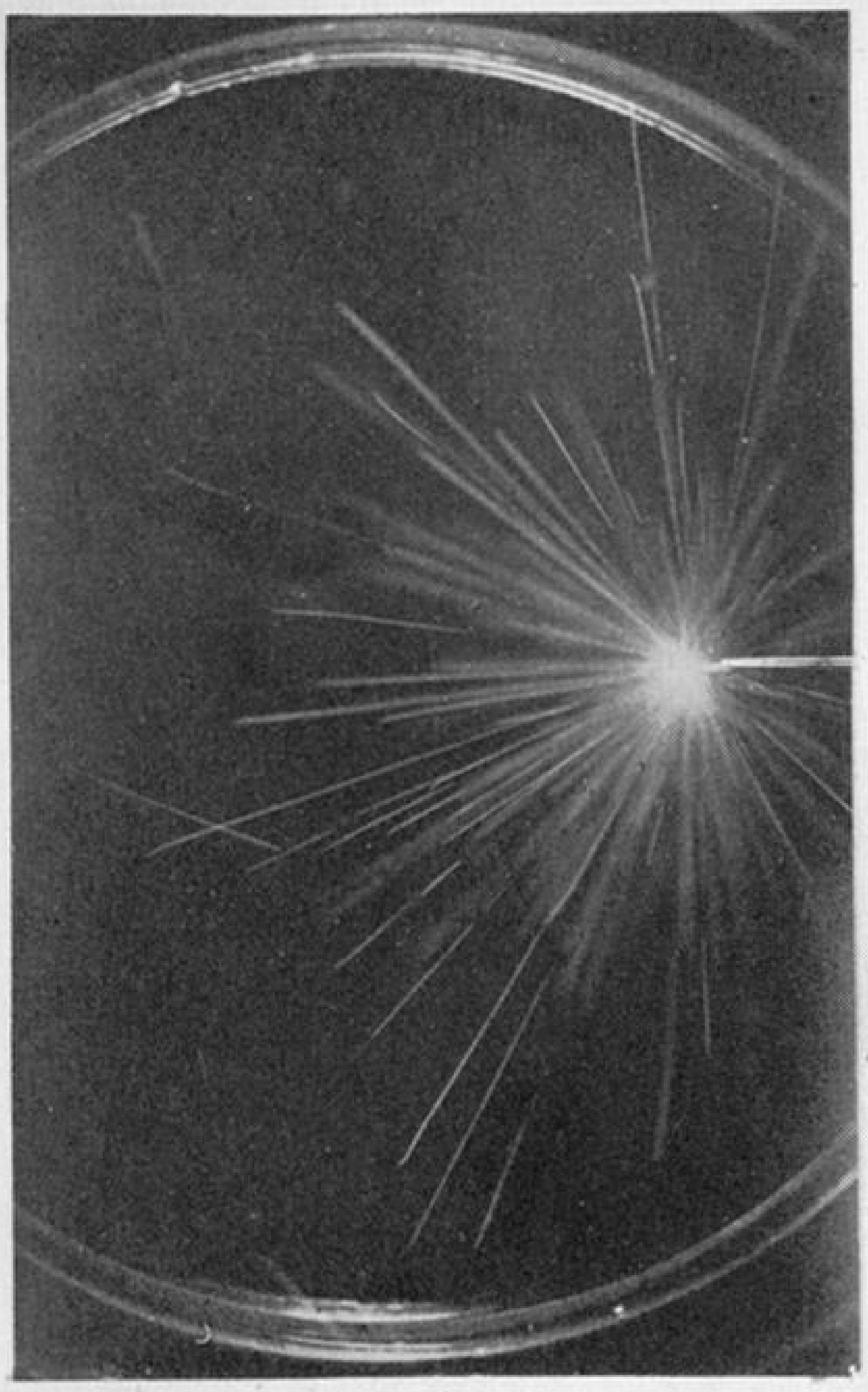

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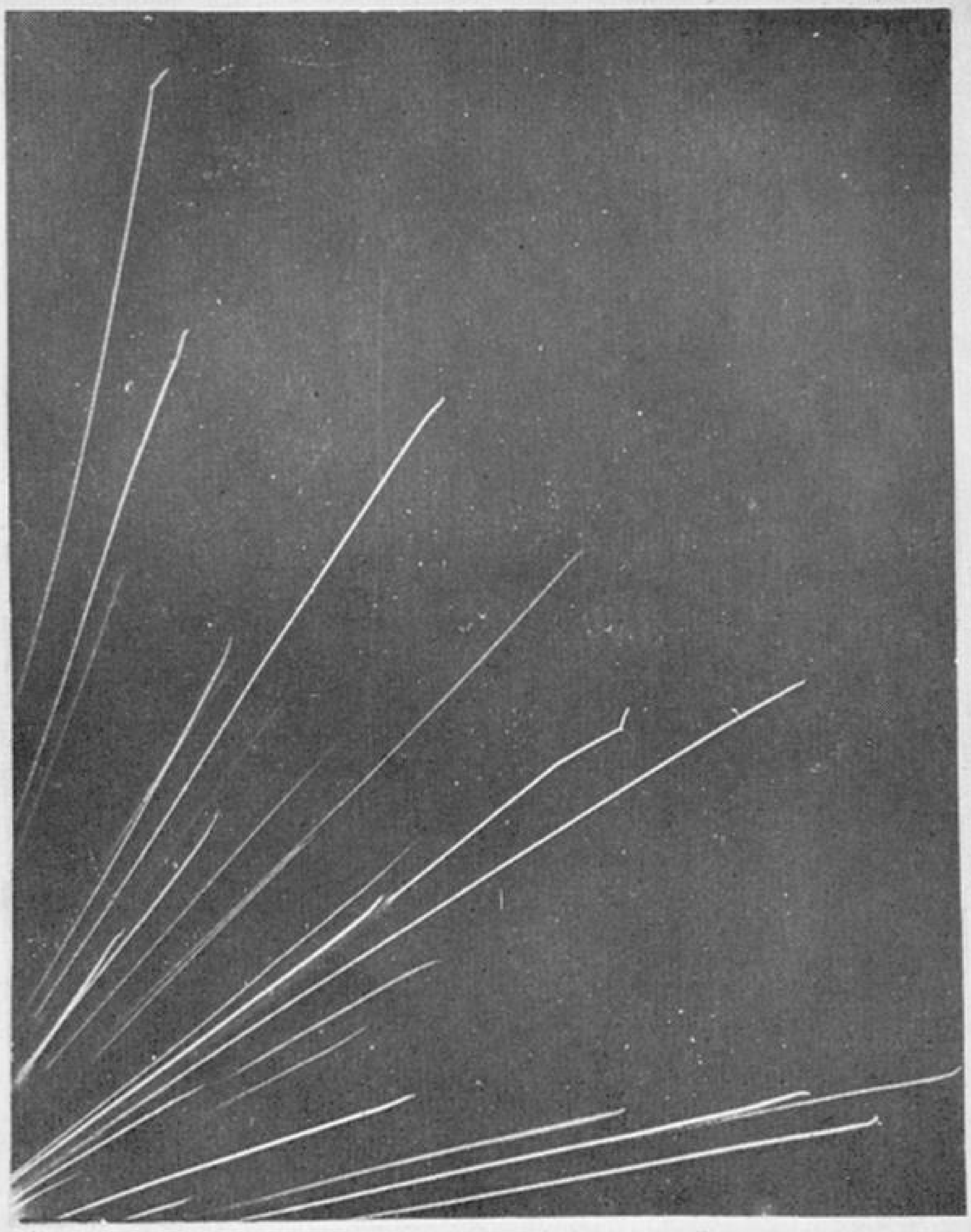

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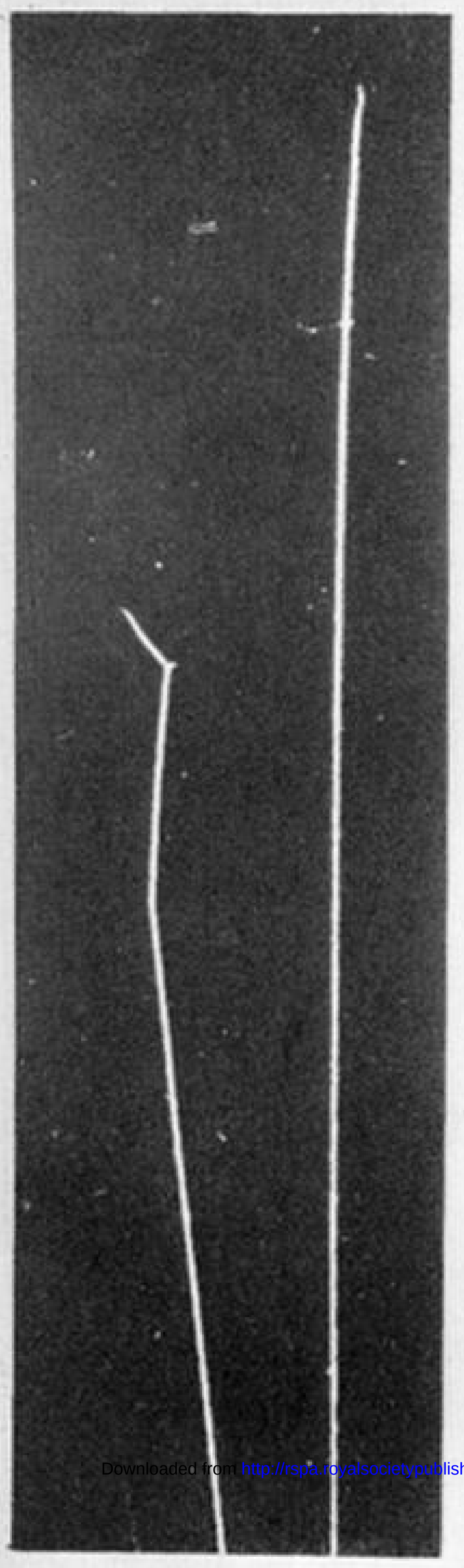

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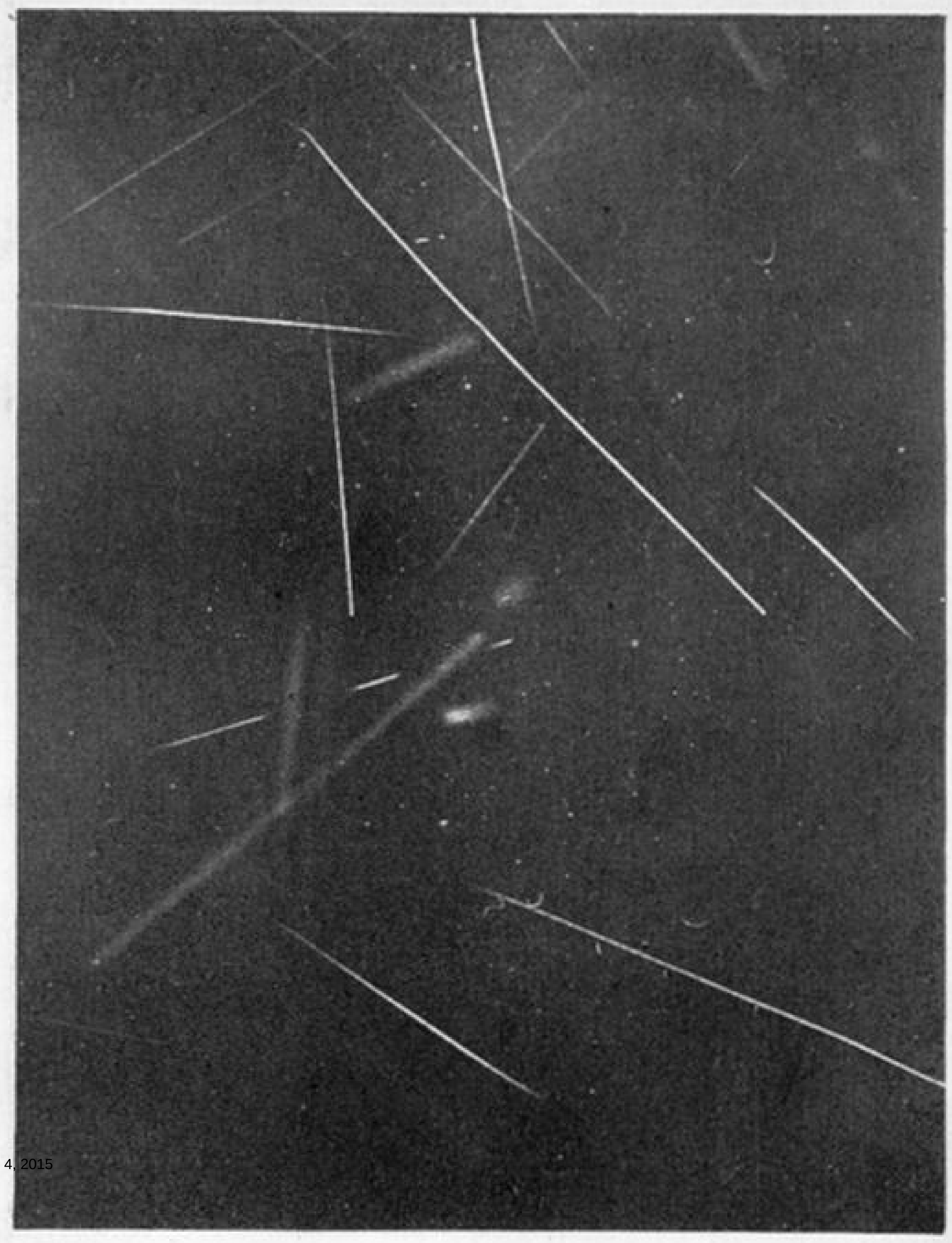

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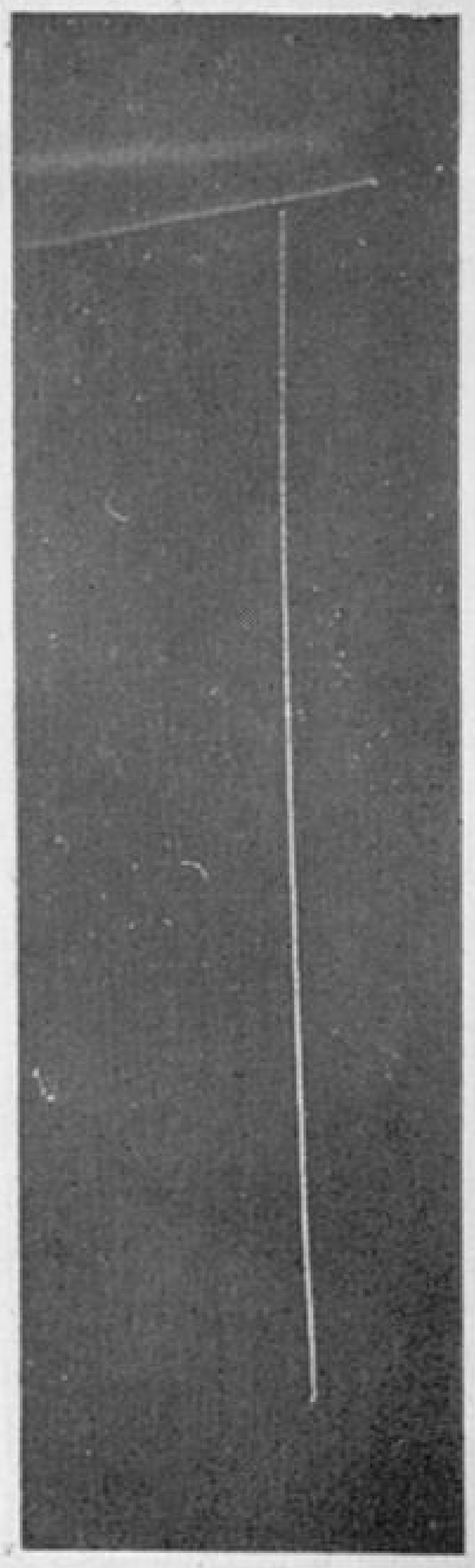

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PLATE 6.

Ionisation by **α**-rays.

Axis of camera vertical ; horizontal layer of 2 cm. in depth illuminated by mercury spark.

Fig. 1. **α**-Rays from radium. Some of the **α**-particles have traversed the air before the expansion, others after the expansion.

$\rho_1 = 0{\cdot}98, \quad v_2/v_1 = 1{\cdot}36, \quad \rho_2 = 0{\cdot}72, \quad V = 40 \text{ volts}, \quad M = 1/2{\cdot}18.$

Fig. 2. **α**-Rays from radium. The **α**-particles have all traversed the air after the expansion.

$\rho_1 = 0{\cdot}97, \quad v_2/v_1 = 1{\cdot}33, \quad \rho_2 = 0{\cdot}73, \quad V = 40 \text{ volts}, \quad M = 1{\cdot}05.$

Fig. 3. **α**-Rays from radium. Enlargement of a portion of fig. 2.

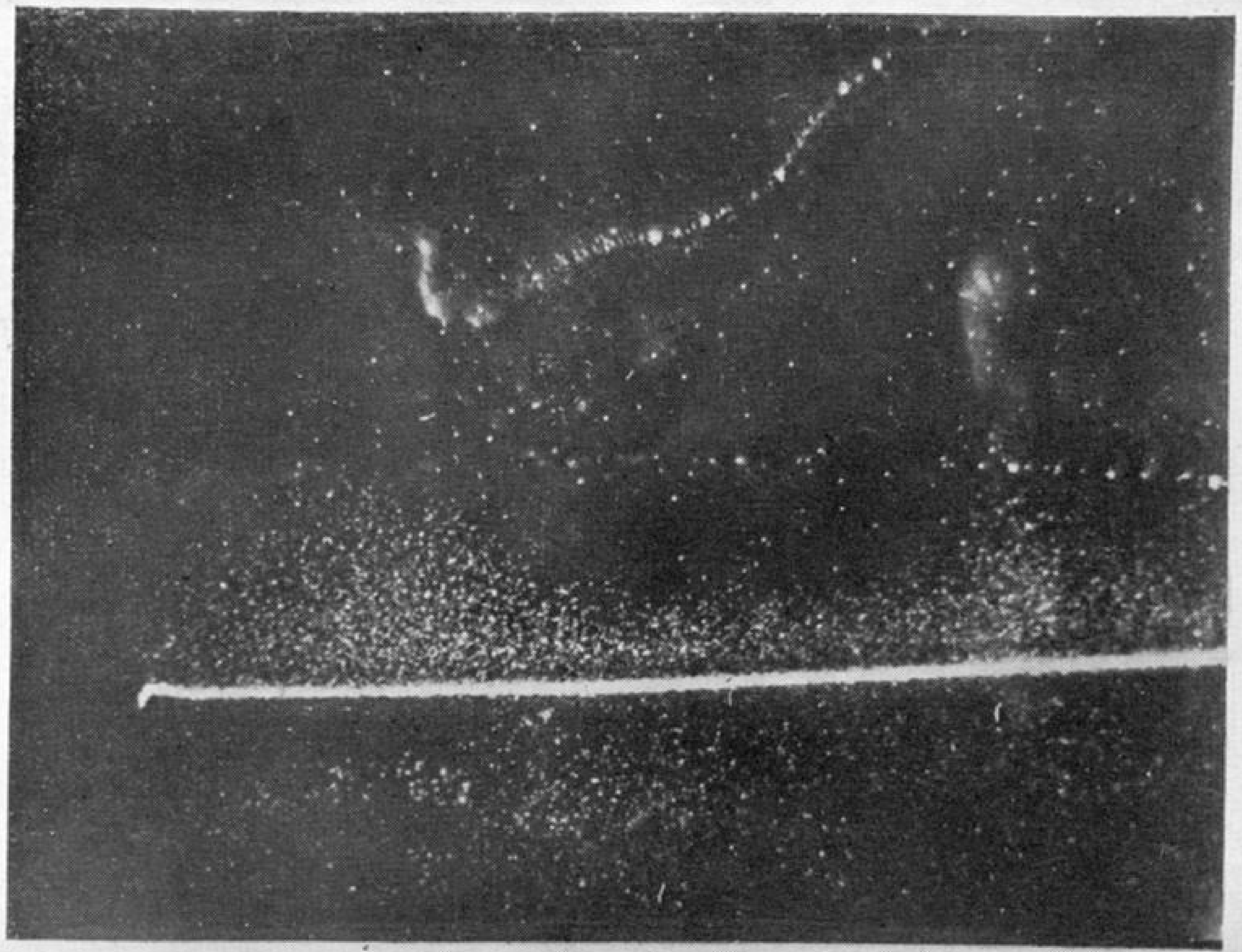
$\rho_1 = 0{\cdot}97, \quad v_2/v_1 = 1{\cdot}33, \quad \rho_2 = 0{\cdot}73, \quad V = 40 \text{ volts}, \quad M = 2{\cdot}57.$

Fig. 4. **α**-Rays from radium emanation and active deposit.

$\rho_1 = 1{\cdot}00, \quad v_2/v_1 = 1{\cdot}36, \quad \rho_2 = 0{\cdot}74, \quad V = 40 \text{ volts}, \quad M = 1/1{\cdot}24.$

Fig. 5. A complete **α**-ray from radium emanation.

$\rho_1 = 0{\cdot}97, \quad v_2/v_1 = 1{\cdot}36, \quad \rho_2 = 0{\cdot}71, \quad V = 40 \text{ volts}, \quad M = 1{\cdot}16.$



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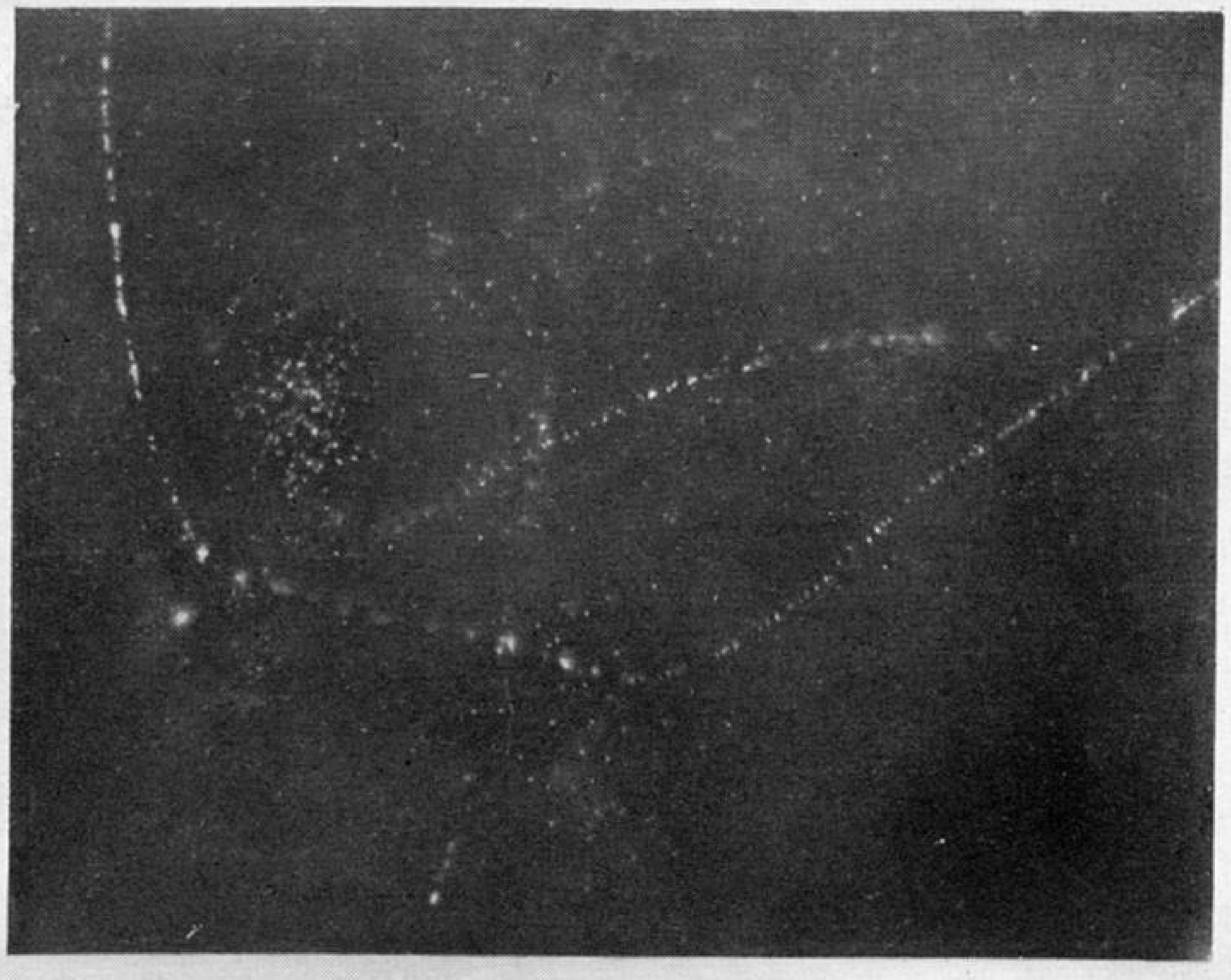

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PLATE 7.

Ionisation by α- and β-rays. The source of the rays is on the right of the picture. Axis of camera horizontal (arrangement (a) of p. 281).

Fig. 1. α- and β-Rays from radium.

$\rho_1 = 0{\cdot}98$, $v_2/v_1 = 1{\cdot}33$, $\rho_2 = 0{\cdot}74$, V = 30 volts, M = 6·0.

Fig. 2. β-Rays produced by γ-radiation.

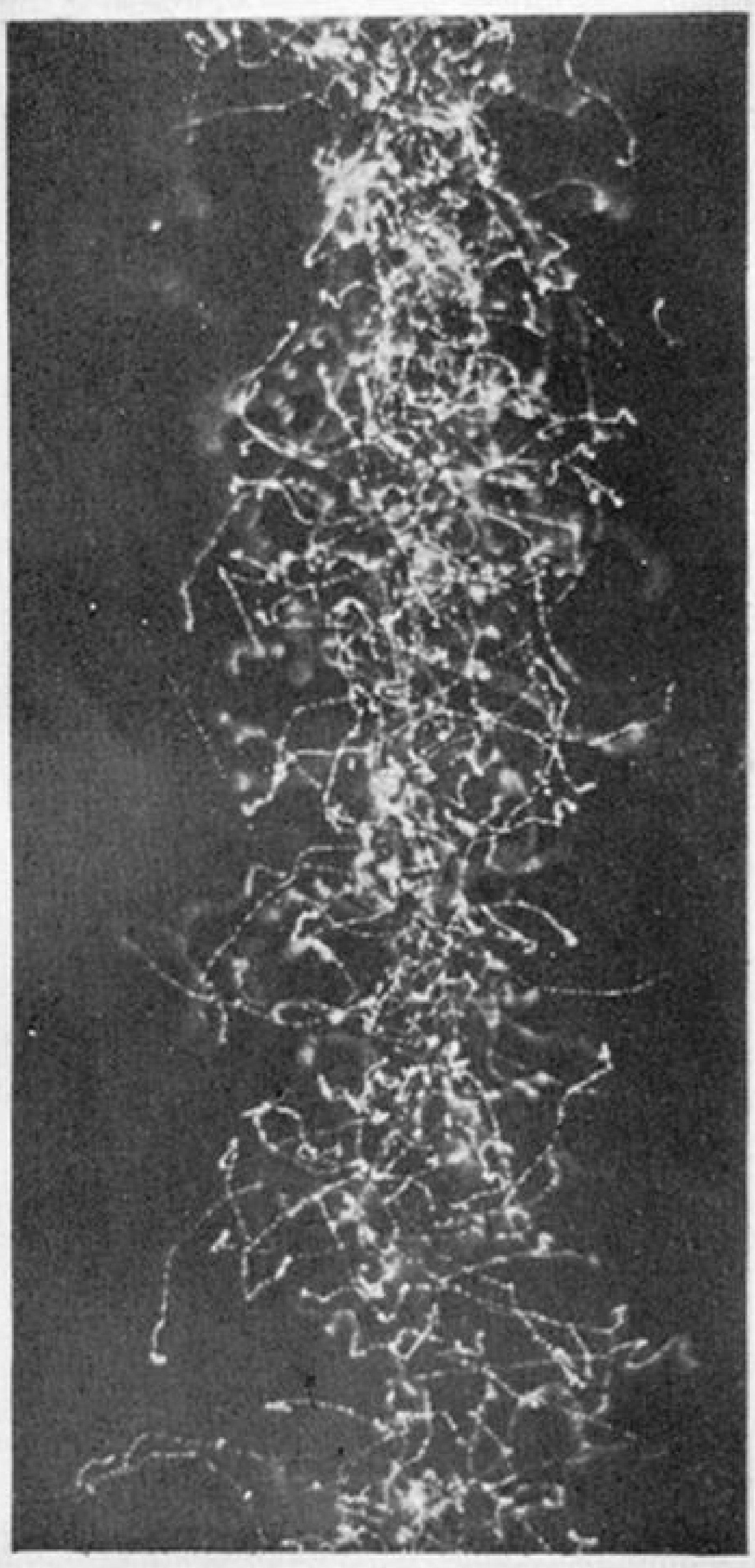
$\rho_1 = 1{\cdot}00$, $v_2/v_1 = 1{\cdot}34$, $\rho_2 = 0{\cdot}75$, V = 40 volts, M = 6·0.

Fig. 3. β-Rays from radium.

$\rho_1 = 0{\cdot}99$, $v_2/v_1 = 1{\cdot}31$, $\rho_2 = 0{\cdot}76$, V = 40 volts, M = 2·45.

Fig. 4. β-Rays. Enlargement of a portion of fig. 3.

$\rho_1 = 0{\cdot}99$, $v_2/v_1 = 1{\cdot}31$, $\rho_2 = 0{\cdot}76$, V = 40 volts, M = 6·0.



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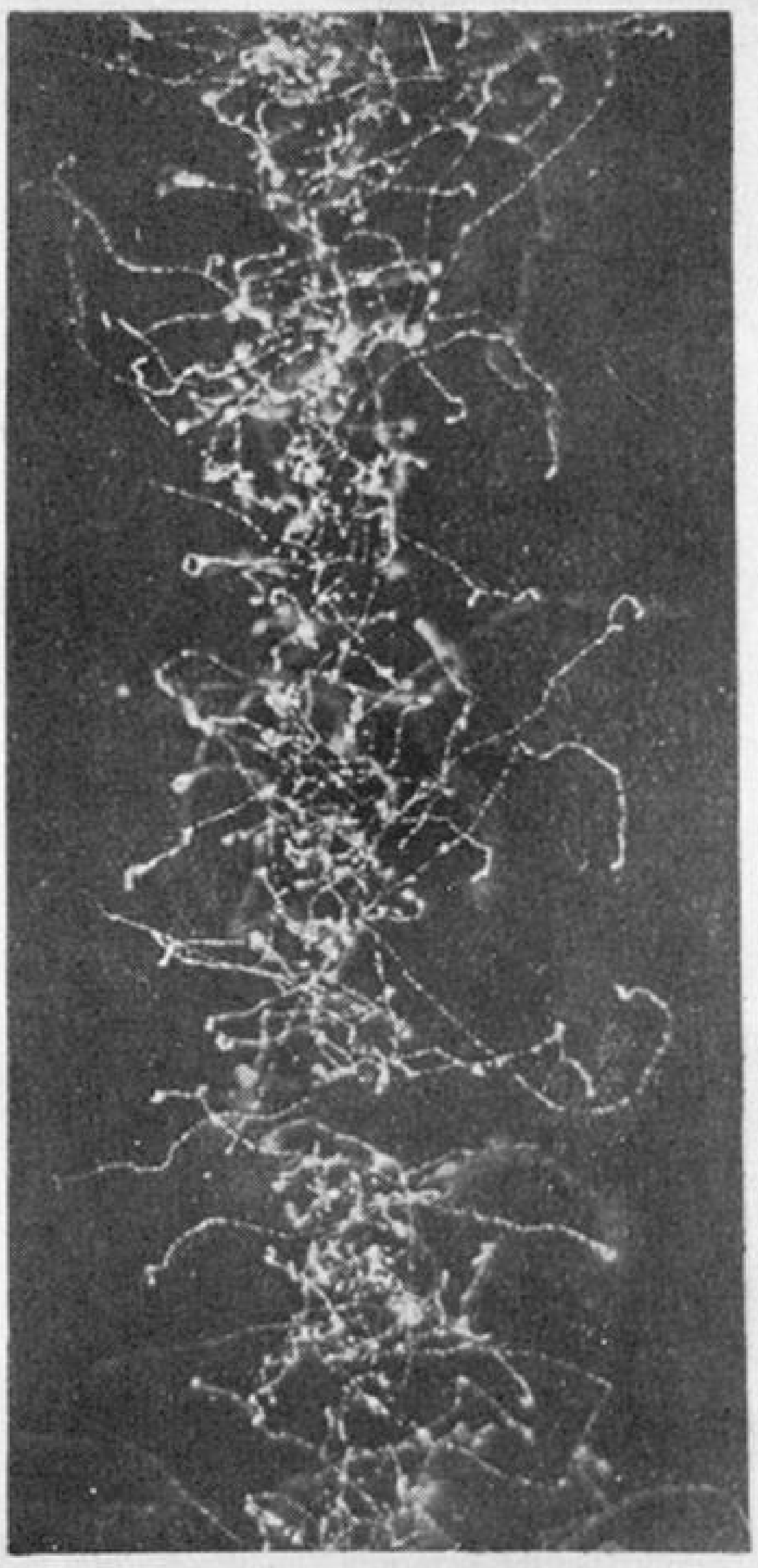

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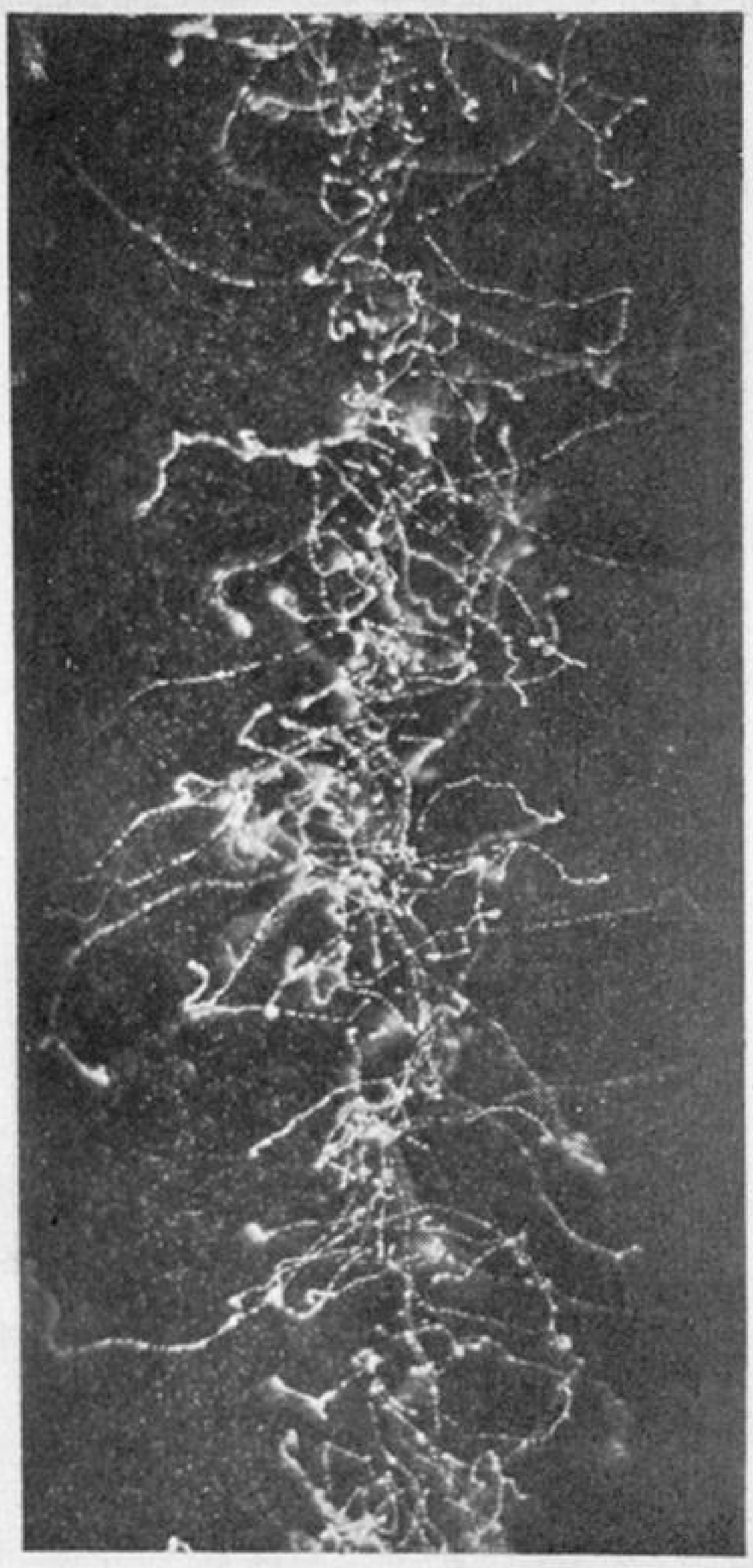

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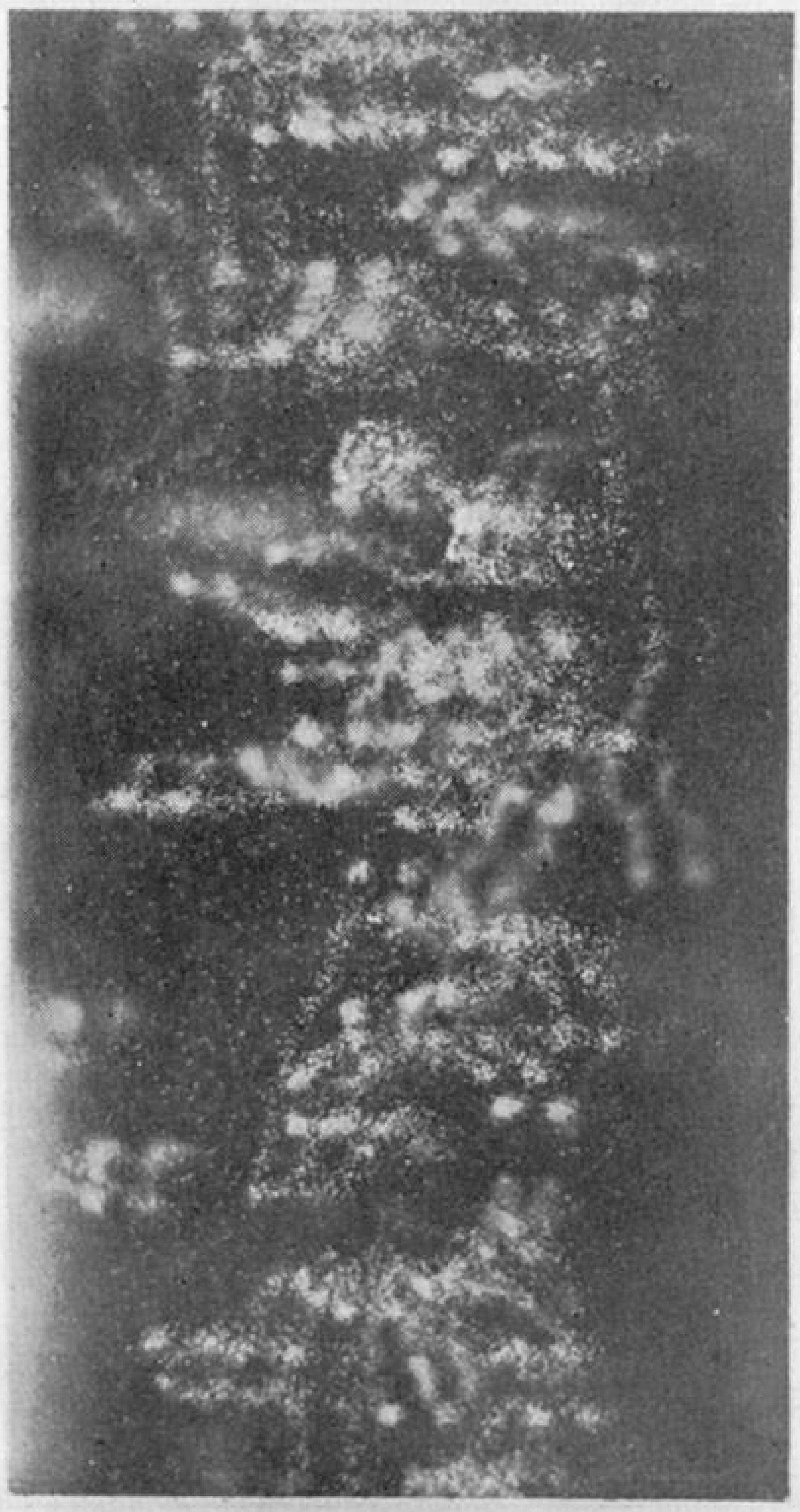

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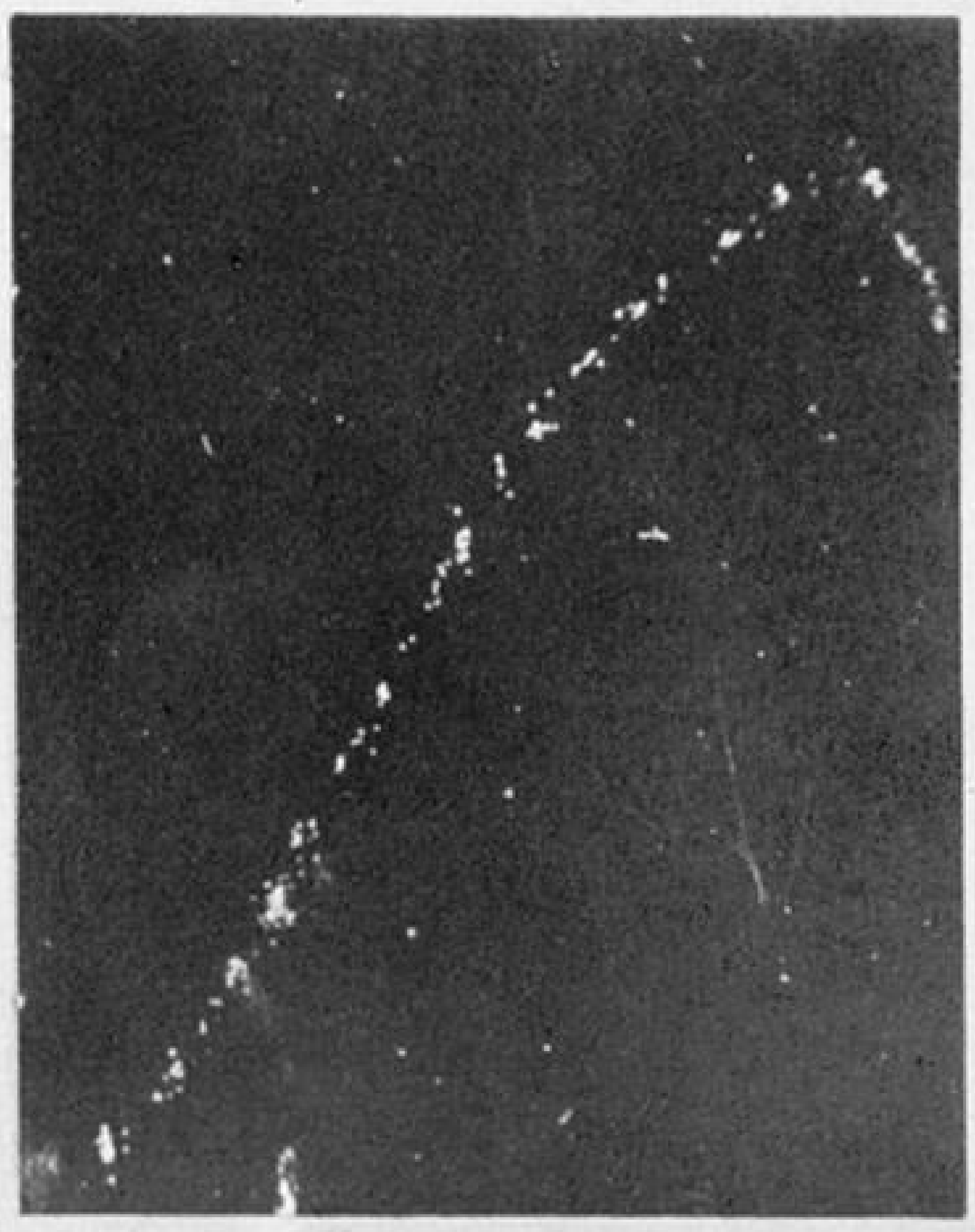

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PLATE 8.

Ionisation by Röntgen rays.

Axis of camera horizontal, X-rays passing from right to left.

In all cases except fig. 5 the X-rays traversed the air after the expansion.

Fig. 1. Ionisation by cylindrical X-ray beam about 2 mm. in diameter.

$\rho_1 = 1{\cdot}00, \quad v_2/v_1 = 1{\cdot}35, \quad \rho_2 = 0{\cdot}74, \quad \mathrm{V} = 4$ volts, $\mathrm{M} = 2{\cdot}45$.

Fig. 2.* Ionisation by X-ray beam about 2 mm. in diameter.

$\rho_1 = 1{\cdot}00, \quad v_2/v_1 = 1{\cdot}34, \quad \rho_2 = 0{\cdot}75, \quad \mathrm{V} = 4$ volts, $\mathrm{M} = 2{\cdot}45$.

Fig. 3. Ionisation by X-ray beam about 2 mm. in diameter.

$\rho_1 = 0{\cdot}93, \quad v_2/v_1 = 1{\cdot}33, \quad \rho_2 = 0{\cdot}70, \quad \mathrm{V} = 40$ volts, $\mathrm{M} = 2{\cdot}45$.

Fig. 4. Ionisation by X-ray beam about 5 mm. in diameter.

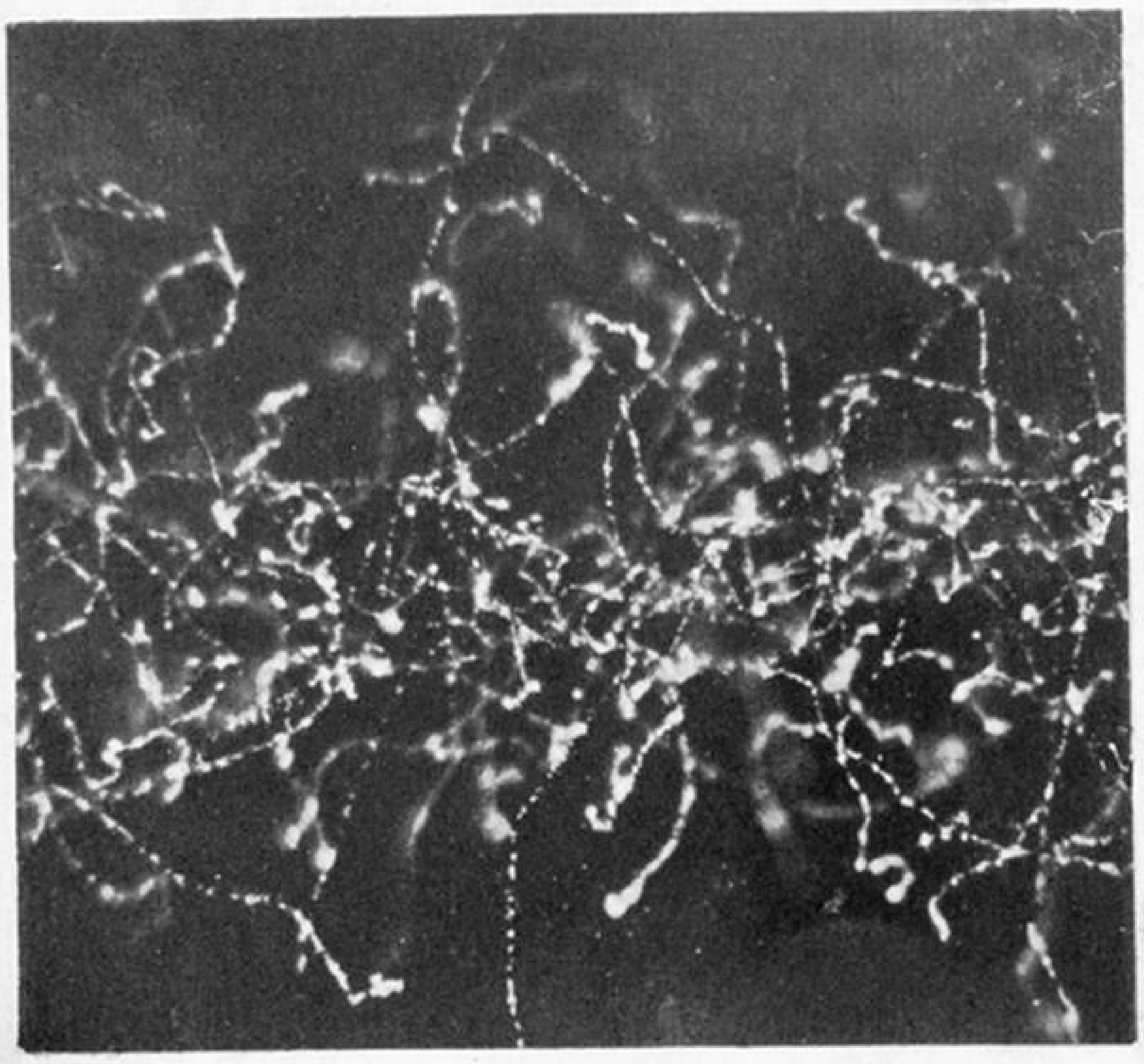
$\rho_1 = 1{\cdot}00, \quad v_2/v_1 = 1{\cdot}36, \quad \rho_2 = 0{\cdot}74, \quad \mathrm{V} = 40$ volts, $\mathrm{M} = 2{\cdot}45$.

Fig. 5. Ionisation by X-ray beam about 5 mm. in diameter. The X-rays traversed the air before its expansion; the positive and negative ions have been separated by the electric field before losing their mobility by the condensation of water upon them.

$\rho_1 = 1{\cdot}00, \quad v_2/v_1 = 1{\cdot}36, \quad \rho_2 = 0{\cdot}74, \quad \mathrm{V} = 40$ volts, $\mathrm{M} = 2{\cdot}45$.

Fig. 6. Portion of fig. 4 enlarged, showing the individual ions produced along a portion of one of the cathode-ray tracks. (The fig. has been turned through 90°.)

$\rho_1 = 1{\cdot}00, \quad v_2/v_1 = 1{\cdot}36, \quad \rho_2 = 0{\cdot}74, \quad \mathrm{V} = 40$ volts, $\mathrm{M} = 14{\cdot}7$.



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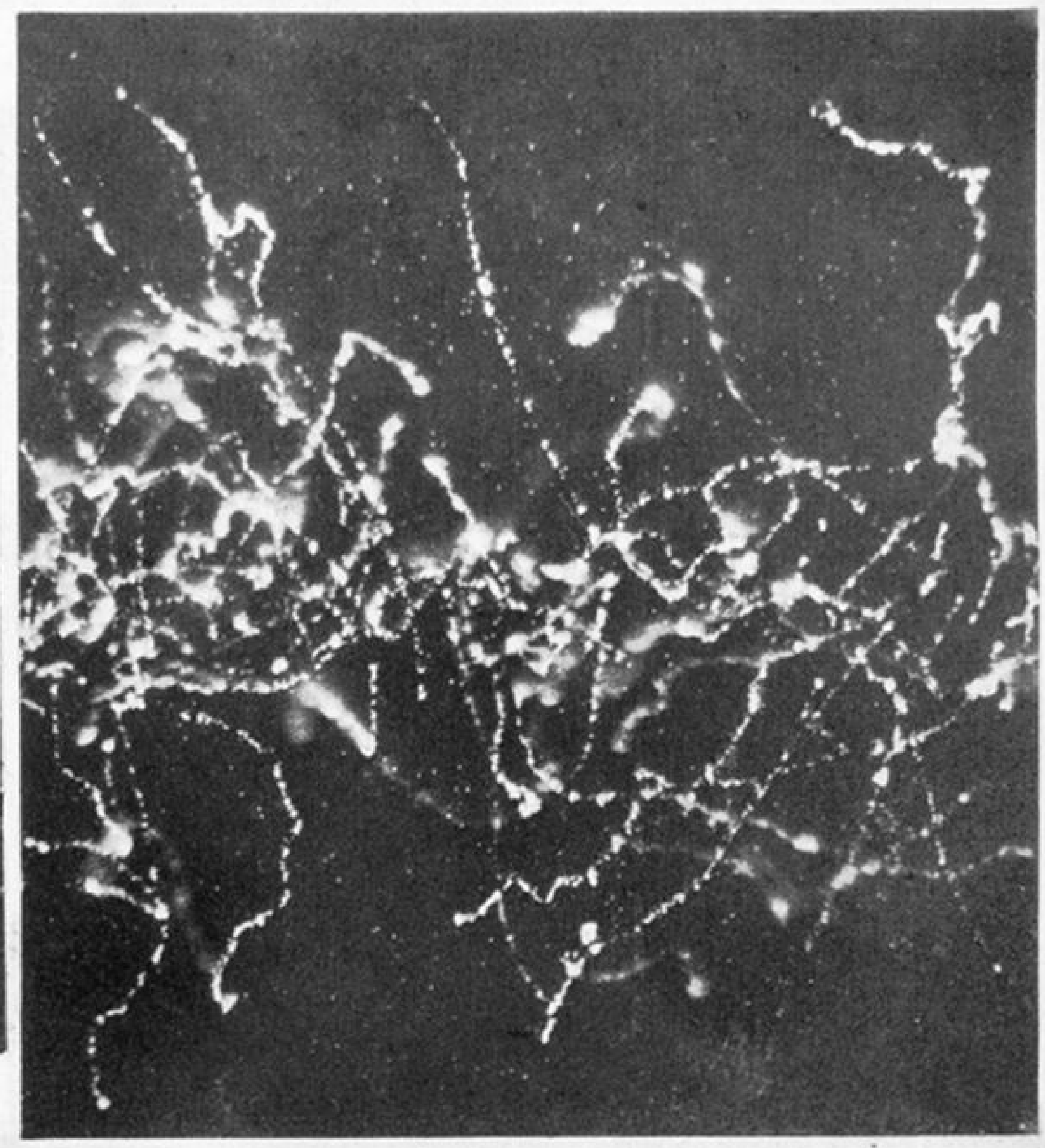

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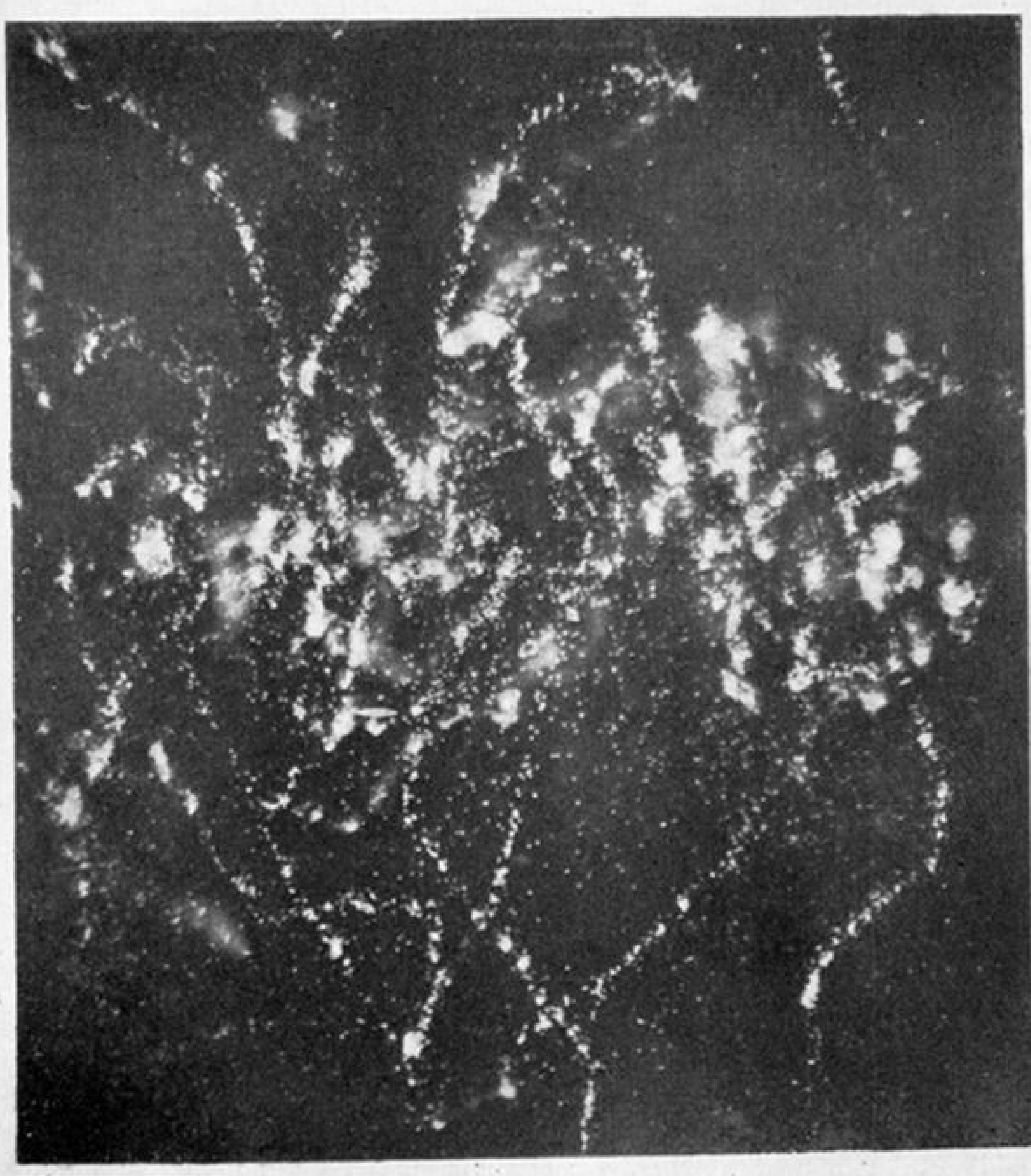

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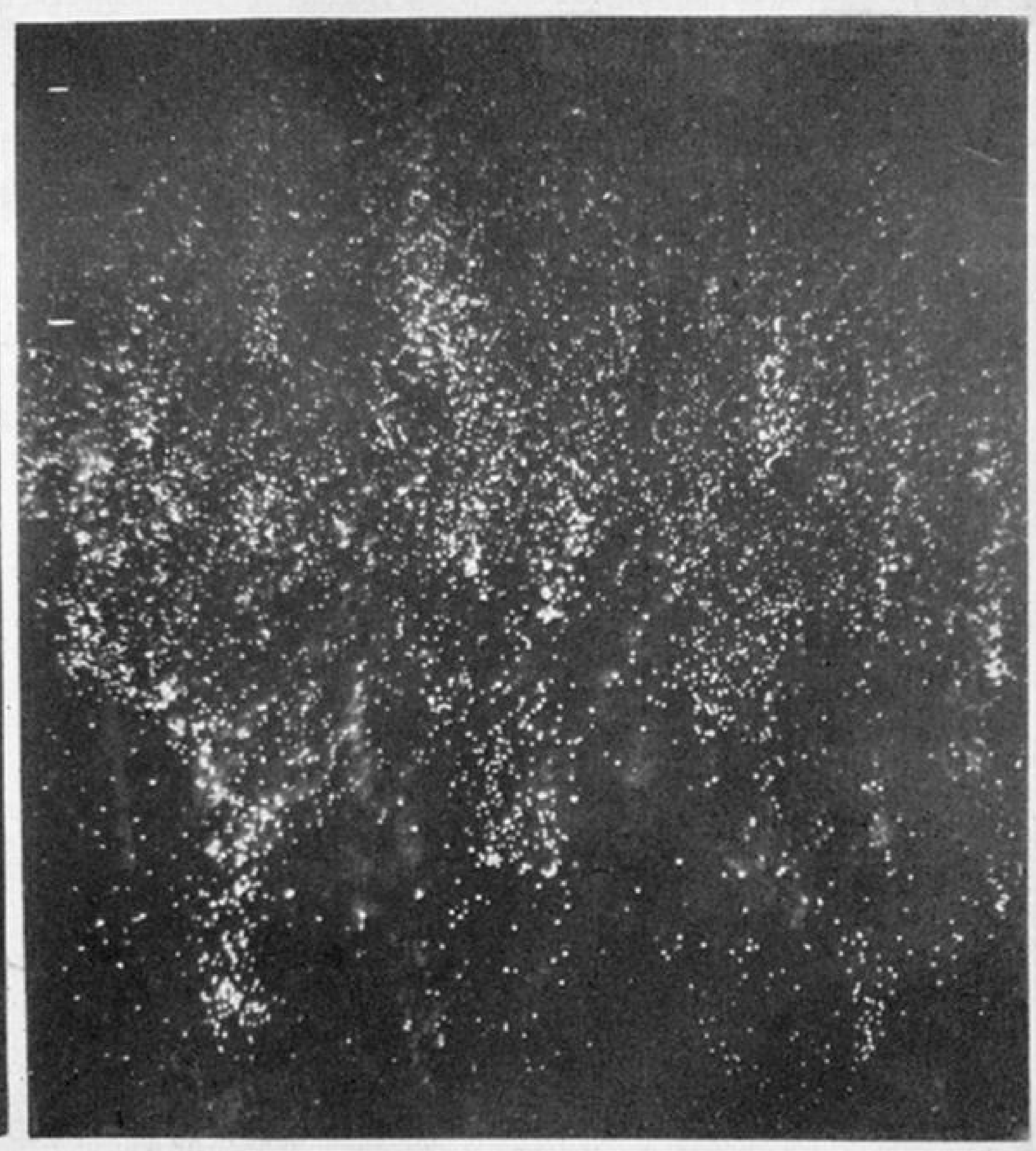

4

PLATE 9.

Ionisation by Röntgen rays. Conditions as in Plate 8; X-ray beam about 2 mm. in diameter. Figs. 2, 3, and 4 belong to a series in which the expansion ratio v_2/v_1 was varied while all other conditions were kept constant.

Fig. 1. Enlargement of a portion of fig. 1, Plate 8.

$$\rho_1 = 1{\cdot}00, \quad v_2/v_1 = 1{\cdot}35, \quad \rho_2 = 0{\cdot}74, \quad \mathrm{V} = 4 \text{ volts}, \quad \mathrm{M} = 6{\cdot}0.$$

Fig. 2. Enlargement of portion of fig. 3, Plate 8. In this, as in all the preceding X-ray pictures, the maximum supersaturation attained has been sufficient to cause the ions to lose their mobility immediately after being set free so that the cathode-ray particles leave sharply defined trails.

$$\rho_1 = 0{\cdot}93, \quad v_2/v_1 = 1{\cdot}33, \quad \rho_2 = 0{\cdot}70, \quad \mathrm{V} = 40 \text{ volts}, \quad \mathrm{M} = 6{\cdot}0.$$

Fig. 3. The maximum supersaturation has only slightly exceeded that required to cause condensation on the positive ions, which have therefore travelled varying distances under the action of the electric field before becoming fixed by condensation of water.

$$\rho_1 = 0{\cdot}92, \quad v_2/v_1 = 1{\cdot}31, \quad \rho_2 = 0{\cdot}70, \quad \mathrm{V} = 40 \text{ volts}, \quad \mathrm{M} = 6{\cdot}0.$$

Fig. 4. Negative ions, which alone are caught with the maximum degree of supersaturation attained, have retained their mobility for varying lengths of time, the cathode-ray trails being therefore drawn out into diffuse sheets under the action of the electric field.

$$\rho_1 = 0{\cdot}90, \quad v_2/v_1 = 1{\cdot}28, \quad \rho_2 = 0{\cdot}70, \quad \mathrm{V} = 40 \text{ volts}, \quad \mathrm{M} = 6{\cdot}0.$$