PROCEEDINGS OF

THE ROYAL SOCIETY.

Section A.—Mathematical and Physical Sciences.

Investigations on X-Rays and β-Rays by the Cloud Method. Part I.—X-Rays.

By C. T. R. Wilson, F.R.S.

(Received June 23, 1923.)

(From the Solar Physics Observatory, Cambridge.)

[Plates 1–12.]

1. *Introduction.*

The method used in these investigations is that which was described in papers communicated to the Royal Society in 1911 and 1912.* The ionising rays are made to pass through moist air, or other gas, in which the water-vapour has been brought into the super-saturated state by sudden expansion of the gas. Each ion liberated becomes at once the nucleus for the condensation of a visible droplet of water; the clouds of drops thus formed are immediately photographed.

Very sharply defined pictures of the tracks of ionising particles—α- or β-rays—may be obtained in this way. When the conditions are suitably arranged, the effects of diffusion of the ions before their mobility has been destroyed by condensation of water upon them, as well as that of subsequent disturbance of the cloud tracks by convection currents in the gas, are negligible: photographs of the path of the ionising particles, practically free from distortion, are obtained. The almost perfect straightness of the track of a very fast β-particle, when it occurs among a crowd of tracks of slower β-particles, gives very convincing evidence that the complicated forms of the latter are not due to instrumental distortion.

* 'Roy. Soc. Proc.,' A, vol. 85, p. 285, and vol. 87, p. 277.

The information contained in the pictures is greatly increased when two cameras are used to take simultaneous photographs. For the purposes of exact measurement relating to some definite problem, such as the branching of α-ray tracks, the arrangement used by Shimizu* and others, in which the axes of the cameras are at right angles, has undoubted advantages. But for the purpose of disentangling the complicated phenomena which attend the passage of β-rays and X-rays through air the stereoscopic method is more effective; it has been used throughout the present investigations.

For the quantitative study of X-rays the cloud method has many advantages over that in which an ordinary ionisation chamber and electrometer are used. It gives directly the number and nature of the β-particles ejected from atoms by the X-rays, and not merely the total ionisation; if each β-ray which is produced by the action of the X-rays represents the absorption of one quantum of radiation the method enables us to deal directly with individual quanta. When the cloud chamber is momentarily traversed by a beam of X-radiation of suitable intensity a picture is obtained (in three dimensions if the stereoscopic method is used) of the tracks of all the electrons ejected from the atoms in a given volume of the gas by the action of the X-rays, primary and secondary. An inspection of the picture shows at once (1) the point of origin of each β-ray, (2) its initial direction (*i.e.*, the direction in which an electron has been ejected from its parent atom by the action of the radiation), (3) the total length of its path or range, (4) the form of the track, its sudden or gradual bends, and the number and direction of emission of any secondary β-rays (branches), and (5) the variation of the ionisation along the track; under favourable conditions the number and distribution of the ions along the tracks may be obtained by direct counting.

A number of stereoscopic pictures of the tracks of α- and β-particles with others illustrating the effects of X-rays, were taken early in 1914, but the work was then interrupted by the War. Some of these pictures were exhibited on different occasions at the Royal Society and elsewhere. Considerable improvements in the details of the method have been introduced since that time. Most of the photographs now reproduced belong to a series of nearly 500 stereoscopic pairs which were taken between December, 1921, and the end of July, 1922.

* 'Roy. Soc. Proc.,' A, vol. 99, p. 432 (1921).

2. *Improvements in the apparatus and method.*

The expansion apparatus which has been used throughout these investigations is that described and figured in the 1912 paper. The following are some of the improvements which have been made in the details of the method.

Cloud-chamber.—In most of the experiments the cloud-chamber consisted of a thin-walled glass cylinder 1·2 mm. thick, 16·5 cm. in diameter, with a plate-glass roof. The height from the top of the brass plunger, which formed the floor, to the roof of the cloud-chamber was generally 3 cm. As in the previous experiments, a marginal ring of tinfoil cemented in between the roof and walls of the cloud-chamber made it possible to maintain a potential difference between the roof and floor. The inner surfaces of the roof and sides of the cloud-chamber were at first coated as in the earlier experiments with a thin layer of gelatine; a small quantity of copper sulphate was added to the gelatine to prevent the growth of mould.

The gelatine lining does not remain permanently effective in preventing the formation of droplets on the interior of the roof and walls of the cloud-chamber. If the upper part of the apparatus remains for some time at a lower temperature than the base, as frequently happens at night owing to changes in room temperature, water distils rapidly from the floor to the roof and sides of the cloud-chamber and collects in drops which are not readily removed. To avoid this difficulty completely it is only necessary to keep the base of the cloud-chamber at a slightly lower temperature than the roof and sides. This is most effectively done by keeping the brass expansion cylinder at a temperature slightly below that of the room by allowing a small flow of tap water to pass continuously through the shallow receptacle in which the expansion cylinder rests.

When the base of the expansion apparatus is cooled in this way the walls and roof remain perfectly clear for an indefinite time, even when the gelatine lining is omitted altogether. Most of the recent photographs have been taken without any gelatine lining on the roof and sides of the cloud-chamber.

The floor of the cloud-chamber, formed by the upper surface of the plunger, remains as in the earlier work covered with a thick layer of gelatine; this is blackened by ink and contains a small quantity of copper sulphate in solution. As in the earlier experiments, a vertical electric field was maintained in the cloud-chamber; the field was directed upwards, and in most cases amounted to about 3 volts per cm.

Cameras.—Two simple box-cameras of fixed focus have been used to obtain the stereoscopic pictures; they are joined rigidly together with the centres of their lenses 5·5 cm. apart. The lenses were Beck "Isostigmars" of maximum aperture F 5·8 and focal length 12 cm.; in many cases the aperture was reduced to F 8 or F 11. The axes of the two cameras converged to a point 40 cm. in front of the lenses for which distance they are also focussed. They have generally been used with their axes in the horizontal plane which passes through the centre of the cloud-chamber.

Illumination.—A Leyden jar discharge through mercury vapour at atmospheric pressure was used as before to illuminate the clouds for the purpose of obtaining the photographs. The mercury discharge tube was as shown in fig. 2 of the 1912 paper, but pointed steel rods were used to close the ends of the silica tubes; the ends of the tubes were inserted in mercury cups. The discharge tube was placed as before at the principal focus of a cylindrical lens.

Photographic plates.—"Imperial process" plates have been used in all the recent work. They are not appreciably less sensitive than rapid plates for the light from the mercury spark, and they have the great advantages of fineness of grain and convenience in use.

Timing Arrangements.—In order that sharply defined pictures may be obtained of the tracks of electrons ejected from atoms byX-rays, it is necessary that the rays should traverse the cloud chamber immediately after the sudden expansion of the gas, and that the drops which condense on the ions set free along the tracks should be momentarily illuminated after a very short interval. As in the early experiments, the momentary flash of X-radiation which sets free the ions in the cloud chamber and the mercury vapour spark which illuminates the drops condensed upon them are produced by the discharge of Leyden jars. The old arrangement in which a falling sphere brought about the two discharges in succession, has been replaced by one in which three pendulums of adjustable period are all released simultaneously. The first (the "expansion" pendulum), as it reaches the lowest point of its swing, opens communication between the vacuum chamber and the space below the plunger, the others (the "X-ray" pendulum and "spark" pendulum) as they reach their lowest points discharge Leyden jars through the X-ray bulb and mercury discharge tube respectively. By adjustment of sliding weights on these pendulums, the X-rays may be made to traverse the expansion apparatus immediately after the expansion is completed, while the illuminating spark follows at an interval long enough to enable the cloud particles to condense on the ions, but not long enough to allow of convection currents causing distortion of the tracks.

When the rays from radio-active substances are being studied, a somewhat larger potential difference (from 20 to 100 volts) has generally been maintained between the roof and floor of the cloud-chamber than in experiments with X-rays. No attempt has been made to confine the exposure of the cloud-chamber to these rays to the period between the production of the super-saturated condition and the passage of the illuminating spark. Such photographs, therefore, show not only the sharply defined tracks of α- or β-particles which have passed through the super-saturated air after the expansion, but also diffuse double tracks in which the positive and negative ions have been separated by the electric field) due to ionising particles which have traversed the air before the expansion.

X-rays.—The source of radiation has throughout the work been an X-ray bulb of old type with a platinum anticathode. The rays were produced (in nearly all cases immediately after the sudden expansion of the air in the cloud-chamber) by the discharge of a large Leyden jar. To make the action of the X-ray bulb regular when used in this way a sufficient resistance had to be inserted in the circuit to make the discharge non-oscillatory. The maximum potential difference across the terminals of the bulb as measured by a spark gap was about 45,000 volts.

The bulb was generally placed with its anticathode at a distance of 46 cm. from the centre of the cloud-chamber and on the same horizontal level, and was surrounded by a thick lead case. A horizontal beam of X-rays, which passed through the centre of the cloud-chamber at right angles to the axis of the stereoscopic camera, was obtained by means of a horizontal lead tube attached to the lead case; the tube was 20 cms. long and was provided at each end with a thick lead diaphragm with suitable aperture. The form and area of cross-section of the beam could be varied by changing the diaphragms, and absorbing screens could be inserted at either end of the tube.

Photographs were taken of the cloud tracks when no screens were inserted (other than a thin mica window in the wall of the cloud-chamber) and with screens of thickness ranging up to more than 2 cm. of aluminium. For a satisfactory study of the β-rays produced by X-radiation it was necessary that their numbers should be kept comparatively small. When no screen was used a convenient number of β-rays was obtained by reducing the X-ray beam to a cylinder of about 0·5 mm. in diameter; when the thickest screens were inserted a square or rectangular beam of about 0·5 square cm. in cross-section was used. The effects of radiations of very different wave-lengths were in this way studied.

A number of experiments were made with the air at pressures considerably less than atmospheric ; the lowest final pressure used was about 10 cms. of mercury.

The experiments have thus far been confined almost entirely to air.

3. *Effects to be expected from the absorption of X-rays in air.*

According to the quantum theory, when X-radiation of definite frequency ν traverses the air of the cloud-chamber and is partially absorbed by it, it loses a certain number of quanta of energy each equal to $h\nu$. Each quantum absorbed by the air causes the ejection of an electron and is thus represented by a β-ray track in the cloud picture. Of the quantum of energy $h\nu$ absorbed by an atom, a part depending on the nature of the atom and the energy level from which the electron is ejected is used in removing the elctron from the atom, the rest is represented by the kinetic energy of the emergent β-particle. The velocities and therefore the ranges of the β-particles ejected by primary radiation of given frequency will thus not all be alike in a mixed gas, like air.

The air of the cloud-chamber contains, besides nitrogen and oxygen, other constituents in quantities sufficient to cause appreciable absorption of X-rays. From what is known regarding the absorption of X-rays we may deduce that the relative number of β-particles ejected by X-radiation of wave length λ from the K-levels of atoms of each of the different constituent elements of the air is approximately proportional to $Z^4 \lambda^3 N$, where Z is the atomic number and N is the number of such atoms per cubic centimetre of the air ; this only applies if the frequency of the incident radiation exceeds the K-absorption limit, otherwise there is no K-absorption. Applying this we find that, while the absorption of X-rays by the hydrogen, carbon dioxide, neon, krypton and xenon present should be relatively negligible, about 60 per cent. of the β-rays which result from ejection of electrons from the K-level should be due to nitrogen, 25 to oxygen, 15 to argon. We should expect also a small number of β-particles to be ejected from the outer levels of atoms of these various elements.

The β-rays originating from these various sources under the action of X-rays of given frequency will have different ranges. When the frequency of the incident radiation is high the differences in the ranges of the β-rays will be unimportant. When, however, the frequency of the incident radiation is not many times that of the absorption limit of argon, as in the experiments with a copper target described in § 4, the range of the β-ray from the K-level of argon will fall far short of that from the K-level of an oxygen or nitrogen atom; the difference between the ranges of the β-rays from the K-levels in oxygen or nitrogen atoms, or from the K- and L-levels in either of these atoms, also ceases to be negligible. We have in such a case a whole series of possible ranges for the β-ray tracks corresponding to the various lines in the magnetic spectrum in experiments such as those of de Broglie.*

The ejection of an electron from an atom by the action of the primary X-rays will in general be followed by the emission of secondary radiation. An atom from which a K-electron has been ejected will emit a quantum of one of its characteristic K-radiations. The K-radiation emitted may give evidence of its existence by ejecting an electron from the K-level of an atom of smaller atomic number or from the outer level of any atom. It would in this way be possible for K-radiation from argon to be absorbed by oxygen with ejection of an electron from the K-level and subsequent emission of oxygen K-radiation; this in turn might be absorbed in ejecting an electron from the K-level of nitrogen and thus causing the emission of nitrogen K-radiation; the final β-ray track will be that of an electron ejected from the outer level of an atom.

A ray produced in air by the action of primary X-rays may have no secondary β-ray associated with it, if it has itself been ejected from among the outer electrons of an atom; it may be expected to have a short range β-ray associated with it, if it has been ejected from the K-level of nitrogen, or it may have more than one if it has arisen in the K-level of oxygen or argon.

As will appear later, the matter is made more complicated by the combined effects of the primary and secondary radiations.

4. *Experiments with "targets" inserted in the path of the X-rays.*

In these experiments a small rectangular piece of metal foil, a few square mm. in area, was fixed at the centre of the cloud-chamber. It was attached to the flattened end of a needle, which projected vertically downwards from the centre of a brass plug closing a circular hole in the glass roof. A cylindrical beam of X-rays, about 0·5 mm. in diameter, was made to strike the centre of the target approximately at right angles.

Plate 1, fig. 1 shows the effects of inserting a copper target, about 8×10^{-3} cm. in thickness, in the path of the narrow pencil of X-rays. The various effects due to the absorption of the primary X-radiations by the copper are well shown. A large number of β-rays radiate from the target; the absence

* 'Journal de Physique,' vol. 2, p. 265 (1921).

of their initial portions is merely due to the heating and other disturbing effects of the copper.

Scattered about in the surrounding air outside the primary X-ray beam are to be seen numerous short β-ray tracks, due to electrons ejected by the secondary radiations from the copper. The greater number of these short tracks, ranging from 1·0 to 2·4 mm. in length in air at $\frac{2}{3}$ of atmospheric pressure, are due to the ejection, by the characteristic K_α and K_β-radiations of copper, of electrons from the different constituents of the air. Small, nearly spherical, clouds about 1/10 mm. in diameter, also appear—the tracks of the slow β-particles ejected by the L-radiations of copper.

Fig. 2, Plate 1, was obtained in an experiment in which the conditions were identical with those just described except that the X-rays had been cut down before entering the cloud-chamber by inserting in their path an aluminium screen 9·2 mm. in thickness. Here no β-rays have been produced by the direct action of the primary X-rays on the air. One β-particle has been ejected from the copper plate, and one β-ray track has been formed in the air, outside the X-ray beam, by the absorption of a quantum of K-radiation from the copper. To produce the quantum of K-radiation which has ejected the β-particle from an atom of oxygen or nitrogen an electron must have been ejected from the K-level of one of the copper atoms; the track of this one electron appears in the photograph. We almost certainly have here the tracks of the two electrons which are associated respectively with the emission and absorption of the same individual quantum of copper K-radiation.

A similar picture was obtained with a platinum target; the length of the β-ray ejected by the secondary radiation indicates that it is due to an L-radiation from the atom of platinum from which the primary β-ray was ejected.

Experiments were also made in which the primary X-ray beam and the target were outside the cloud-chamber. The target was an inclined metal plate placed immediately above an aluminium window in the centre of the roof of the cloud-chamber; a horizontal beam of X-rays was incident upon it. The photographs obtained with copper and silver targets showed well the different effects of the K-radiations from these metals.

The ranges of the β-rays produced in air by the K-radiations from copper varied between about 0·6 mm. and 1·7 mm., those produced by the silver K-radiations between 8 mm. and 16 mm. In both cases the tracks could be grouped into three classes according to their ranges; these classes correspond to the different lines in a β-ray spectrum. The range which recurred with maximum frequency is (in accordance with the greater intensity of the K_α lines in the X-ray spectrum) taken to be due to the ejection of an electron from the K-level of an oxygen or nitrogen atom by the K_α-radiation from the metal; the group of maximum range is taken to be due to the ejection of an electron from the same elements by the K_β-radiation. The β-rays of shortest range produced by the K-radiations have probably been ejected from the K-level of argon atoms; their ranges are in accordance with this view.

The ranges of the β-rays ejected from oxygen or nitrogen by the K_α and K_β-rays from copper are about 1·3 mm. and 1·7 mm. respectively; those ejected by the K_α and K_β-radiations of silver have ranges of about 11 mm. and 15 mm.

Putting the kinetic energy of the ejected β-particle equal to the difference between the energy ($h\nu$) of the incident radiation and that required to eject an electron from the K-level of nitrogen we have in the case of the copper K-radiations, $K_\alpha\,(\mathrm{Cu}) - K\,(\mathrm{N}) = 7{,}700$ volts, $K_\beta\,(\mathrm{Cu}) - K(\mathrm{N}) = 8{,}600$ volts. Similarly the kinetic energies of the β-particles ejected by the silver K_α and K_β-radiations are 21,700 and 24,600 volts approximately.

The results of these measurements of the mean ranges of β-particles of different kinetic energies are represented approximately by the formula $V = 21{,}000\,R^{\frac{1}{2}}$, where V is the kinetic energy of the particle expressed in volts and R its range in centimetres, measured along the track, in air at atmospheric pressure. The experimental results are thus in approximate accordance with Whiddington's fourth-power law* connecting the range and velocity of a β-particle. The velocity of a β-particle of range 1·5 cm. is nearly $\frac{1}{3}$ of that of light and the kinetic energy given by the relativity formula,

$$m_0c^2\left(\frac{1}{\sqrt{1-\beta^2}}-1\right)$$

already exceeds $\frac{1}{2}m_0v^2$ by nearly 10 per cent.; for higher velocities [the relation between range and kinetic energy is likely to be less simple.

The tracks of β-particles, such as those due to aluminium K-radiations or copper L-radiations, of which the kinetic energy is less than 2,000 volts are of too short range (less than 1/10 mm.) to be measurable; they appear in the pictures as small, nearly spherical, clouds.

5. *Different classes of β-rays produced in air by X-rays.*

When the air in the cloud-chamber is exposed to hard radiation—the wave-length of which is for example about 0·4 A°—three classes of β-ray tracks

* 'Roy. Soc. Proc.,' A, vol. 86, p. 360 (1912).

may be distinguished :—(*a*) "Long" tracks having a range of several centimetres; (*b*) "sphere" tracks, small, almost spherical, cloudlets, 1 or 2-tenths of a millimetre in diameter; and (*c*) tracks of 1 or 2 mm. in range, of which the initial direction approximately coincides with that of the primary X-ray beam. From their characteristic appearance when a number of them are present I have been in the habit of recording the tracks of this last class as "fish" tracks; the tail of the "fish" is directed towards the source. Figs. 3 and 4 contain examples of the three classes of tracks.

The "long" tracks are undoubtedly the paths of electrons ejected from atoms in most cases by the direct action of the primary beam, each having absorbed one quantum of energy corresponding to the frequency of the primary radiation. The range of these tracks depends on the frequency of the primary radiation and has been used for the purpose of estimating that frequency.

The "fish" tracks are also—as the direction of ejection indicates—almost certainly due to the direct action of the primary radiation; but the energy of the ejected electron is only a small fraction of that of a quantum of the primary radiation, and these tracks do not appear when the wave-length of the incident radiation exceeds 0·5 A°. They are almost certainly connected with the phenomena which have led Barkla and others to postulate the existence of a "J"-radiation; again to explain other phenomena relating to secondary radiations A. H. Compton has suggested the possibility of the forward ejection of short range β-particles.

"Sphere" tracks are probably in all cases merely the tracks of very short range β-rays; any β-particle with energy less than that corresponding to about 2,000 volts will produce such a track. Some of the sphere tracks which are formed in air exposed to X-rays of high frequency are probably produced in the same way as the fish tracks; intermediate comma-like forms are of frequent occurrence. Other sphere tracks are undoubtedly due to the ejection of electrons by secondary X-rays. A sphere track is frequently situated close to the origin of a long track and is sometimes outside the primary beam of X-rays. The ejection of the short range β-particle may in this case be due to the characteristic radiation from an atom, from the K-level of which the primary X-radiation has expelled the β-particle which produced the long track. There are, however, other cases of association of β-rays in pairs which cannot be explained so simply. (See section 8.)

6. *Direction of ejection of the β-particles.*

(*a*) *Polarisation.*—In almost every stereoscopic picture of the tracks of β-particles produced by a horizontal beam of X-rays, in which a convenient number (10 to 30) of tracks are present, several are found to start, as nearly as can be distinguished, in directions parallel to a vertical plane containing the axis of the X-ray beam. The cathode ray stream in the X-ray bulb was always directed vertically upwards, so that the vertical plane is that in which we should expect the electric vector in the polarised portion of the radiation to lie.

About 20 per cent. of the β-particles were found to be ejected in the vertical plane. Barkla found about 20 per cent. of the radiation from the X-ray bulb used by him to be polarised.

That a partially polarised beam of X-rays shows a deficiency of β-rays starting in directions lying in the plane of polarisation and an excess starting in direction lying in the perpendicular plane has been confirmed by some more recent experiments. In these a horizontal beam of primary X-rays was incident on a cylinder of paraffin wax placed above an aluminium window in the roof of the cloud chamber; a scattered beam partially polarised in the vertical plane passes vertically downwards into the cloud-chamber.

(*b*) *Forward component in velocity of ejection.*—In the photographs obtained in 1912 no systematic preponderance was evident in the number of β-rays which were ejected with a forward rather than a backward velocity relative to the direction of the X-rays which caused their ejection; this was perhaps mainly due to the tracks being too closely crowded together. Such a preponderance of β-particles which have a forward component in their initial velocity is a striking feature in most of the stereoscopic pictures which have recently been obtained, *e.g.*, fig. 6, Plate 5.

A study of individual tracks shows at once that the forward component in the velocity of a β-particle does not depend simply upon its velocity of ejection, *i.e.*, upon the wave-length of the radiation absorbed. The β-ray tracks may be divided into three easily distinguishable classes, according as the forward component is positive, zero or negative.

It is remarkable that quite a considerable proportion of the tracks belong to the 2nd class, *i.e.*, they are due to β-particles which have been ejected almost exactly at right angles to the X-ray beam. The tracks belonging to the first class, which is the most numerous, have in nearly all cases a comparatively large forward component, very frequently approximately equal to the lateral component; *i.e.*, the most frequent direction of ejection makes an angle of about 45° with that of the X-ray beam. Fig. 3, Plate 2, contains examples of the two first classes in the centre of the picture. Again the third class consists mainly of β-rays with a backward component comparable with the lateral components. Cases in which there can be any doubt as to the class to which a β-ray is to be assigned are very rare.

The results of the examination of 1,148 tracks with regard to their initial direction are given in Table I.

Table I.

Average range (millimetres)	Energy kilovolts.	Total number of tracks.	Tracks with positive, zero and negative forward components.					
			Number in each class.			Number in each class per 100 tracks.		
			+	0	−	+	0	−
20–30	30–36	223	155	37	31	69	17	14
15–20	25–30	662	385	136	141	58	21	21
7–15	17–25	202	106	56	40	52	28	20
2–7	9–17	61	28	21	12	45	35	20

The last columns of Table I show very clearly that the percentage of β-ray tracks which have a forward component in their initial direction increases rapidly with increasing velocity and range of the ejected electron, *i.e.*, with increasing frequency of the incident radiation. This increase is mainly at the expense of the β-rays with zero forward component.

The difference between the effects of radiations of higher and lower frequencies on the average direction of ejection lies much more in the relative number of electrons which start with a forward component than in the direction of ejection of those which have the forward component. Tracks which have a forward component, even if their range is less than 1 cm., start most frequently in directions inclined at angles of about 45° to that of the X-ray beam. The forward inclination is in this case, it may be remarked, much larger than that deduced according to the view that the quantum of radiation absorbed passes on the whole of its momentum to the ejected electron.* On the other hand tracks of long range, 3 cm. or more, frequently start at right angles to the X-ray beam; or again their initial direction may have a larger backward component.

Tracks with a very large forward inclination are, however, mainly of long

* Richardson, 'Electron Theory of Matter.'

range. A few such tracks start almost along the direction of the X-rays; on the other hand a few long-range tracks start almost in the opposite direction, *i.e.*, towards the source of the X-rays.

In the above account of the phenomena relating to the direction of emission of the ejected β-particles it is to be noted that the special type of tracks in which the forward component in the velocity is most marked—the "fish" tracks—has not been included.

A thorough investigation of the direction of ejection of β-particles of all ranges with a fairly accurate measurement of the angles is likely to lead to interesting results.

7. *Short-range β-rays: "sphere," "comma" and "fish" tracks.*

The intensity of the ionisation in the final tenth of a millimetre of the range of an ordinary β-ray in air is so great, and the deviations so frequent and large, that its cloud track generally ends in a more or less spherical bunch or knot, consisting of drops too closely packed for resolution. Any β-ray of shorter range than about 1/10 mm. (*i.e.*, of energy rather less than that corresponding to 2,000 volts) is represented by a cloud track which consists of the sphere alone. If the range is slightly greater the initial portion of the track may show as a small tail projecting from the sphere; we thus get a comma-like track. If the range is a little longer the form of the track is such that, when a number appear together with their "tails" all pointing in one direction, they resemble a shoal of small fishes.

In air exposed to X-rays such "sphere" tracks and "fish" tracks together generally considerably exceed in number the long tracks, if the latter have an average range exceeding 1·5 cm. (figs. 3 and 4, Plates 2 and 3).

The fish tracks and comma tracks are absent, and the sphere tracks are relatively few, if the long tracks are all of range as short as 7 mm. (Fig. 5, Plate 4.)

When the frequency of the incident radiation is increased beyond a point where the ordinary β-ray tracks have a range of about 1 cm. the number of sphere tracks begins to increase rapidly and soon becomes comparable with that of the long tracks. With a further increase in the frequency of the radiation some of the spheres develop tails on the side next the source and become comma-shaped. When the X-rays are hard enough to eject β-particles of 1·5 cm. range, fish tracks of ranges up to about 0·4 mm. appear; their range increases as the frequency of the incident radiation is increased, but rarely exceeds 1·5 mm., even when the long tracks have a range exceeding 3 cm.

An estimate of the energy and frequency of the radiation absorbed in ejecting the electrons which produce the comma and fish tracks may be obtained from the ranges of ordinary β-particles ejected at the same time. It has, however, to be remembered that the incident radiations were far from homogeneous, so that the radiation absorbed in producing the fish tracks may have been of somewhat different frequency from that which corresponds to the mean range of the long tracks. But the data are sufficient to show that the difference between the energy of a quantum of the incident radiation and the kinetic energy of the ejected electron to which a fish track is due is between 20,000 and 30,000 volts; and that the maximum wave-length of the radiation consistent with the production of the fish tracks is between 0·4 and 0·6 A°.

It is just to this region of the spectrum that Barkla* and Crowther† have assigned the wave-length of the "J"-radiations, of which they found evidence in certain anomalies encountered in the study of absorption and scattering in elements of low atomic number.

Before it is concluded that there are electrons in the atoms of oxygen or nitrogen, of which the work of ejection is between 20,000 and 30,000 volts, or on the other hand, that this difference between the energy of a quantum of the incident radiation and that of the short range β-ray is represented by scattered radiation—in accordance with a suggestion made by Compton—some other possibilities must be considered.

It might in the first place be objected that the short-range β-tracks may be due to a constituent of correspondingly long wave-length remaining in the incident radiation. The two classes of tracks (of a range of several centimetres and of a fraction of a millimetre) obtained, for example, when the radiation has previously been filtered through 2 cm. of aluminium, or its equivalent in copper, tin or lead, might be due to the residual primary radiation and to the characteristic radiations from the screening material respectively. But the short range tracks are confined almost exclusively to the primary beam as defined by the two diaphragms at the ends of the collimating tube, whether the screen is placed between the X-ray bulbs and the collimating tube or between the collimating tube and the thin glass of the cloud-chamber. In the latter case the fluorescent X-rays should radiate in all directions from the screen, not only along the direction of the primary radiation. Again the nature and relative number of the short tracks was not found to depend on the material of the screen.

* 'Barkla, 'Phil. Trans.,' A, vol. 217, p. 315; 'Phil. Mag.,' vol. 34, p. 270 (1917).

† Crowther, 'Phil. Mag.,' vol. 42, p. 719 (1921).

The fish and comma tracks might also be attributed to the ejection of electrons from the K-levels of atoms of the rare gases of the atmosphere of higher atomic number, the relatively small number of which would be to some extent counterbalanced by the very rapid increase of absorption with increasing atomic number. The K-absorption limit of xenon falls not far below the lower limit found above for the effective wave-length. The number of the short-range tracks—which are approximately as numerous as the long tracks when the frequency of the incident radiation is high—is, however, far too great for this source to be a possible one.

A "fish" track or comma track is thus almost certainly due to the ejection of an electron from an atom of one of the common constituents of the air by radiation of the same frequency as that to which the long tracks are due. If a whole quantum of the incident radiation is absorbed in the ejection of an electron from an atom of oxygen or nitrogen, the electron must have come from an energy level below that of the K-electrons, the difference between this "J"-level and the K-level being represented by 20 or 30 kilovolts; *i.e.*, the electron must have been very closely attached to the nucleus.

There are great difficulties in the way of accepting the view that there is a "J" energy level in the atom, and that the difference between the kinetic energies of the electrons producing the long and short tracks respectively represents a difference in the energies required to remove electrons from the J and K energy levels. The fact that these short-range electrons are ejected very nearly in the forward direction is of itself sufficient to indicate that the process of ejection differs essentially from that of the ejection of the ordinary long-range electron.

To account for various phenomena relating to the wave-length and distribution of secondary X-rays A. H. Compton has suggested the possibility of just such a forward ejection of electrons as actually occurs in these "fish" tracks.

Compton* points out that if there is a type of scattering in which a whole quantum of radiation is dealt with by one electron of the atom, this electron may be expected to receive the whole momentum, $h\nu/c$, carried by the radiation. If we suppose that the scattered radiation is emitted by the electron in all directions—not localised in a bundle—then the electron will gain by the scattering process a momentum, $mu = h\nu/c$, in the forward direction and a kinetic energy $\frac{1}{2}\, mu^2 = \frac{1}{2}\, h\nu u/c$.

Let us suppose that it is only the K-electrons which are effective in this

* "Secondary Radiations produced by X-rays," 'Bull. Nat. Research Council,' Washington (1922).

type of scattering in elements of low atomic number like oxygen and nitrogen. There will then be no ejection of the electron from the atom unless $\frac{1}{2}mu^2$ exceeds the energy corresponding to the K-absorption limit—the equivalent of about 380 volts in the case of nitrogen. If we calculate the energy of the incident radiation $h\nu = cmu$ corresponding to this value of $\frac{1}{2}mu^2$ we obtain $h\nu = 19{,}800$ volts. This may be regarded as giving the calculated minimum energy of the radiation which is required to produce rudimentary "fish" tracks; at this stage such a track would be represented by a single pair of ions. Similarly 28,000 volts would give to the scattering electron twice the energy required to eject it from the atom, and a typical "sphere" track would result; about 50,000 volts would be required to give a properly developed "fish" track.

The agreement between the observed phenomena and these applications of Compton's theory lends strong support to that theory. It is a question of great interest whether the quantum of radiation scattered by an electron is emitted in all directions (with a continuous wave front) as assumed above, or in one direction only as Compton suggests. In the latter case the direction and magnitude of the resultant momentum of the electron will depend on the direction in which it emits the radiation.

Information on this very fundamental question may possibly be obtained from a more thorough study of the initial directions and ranges of the fish tracks produced by homogeneous radiation of known wave-length.

Many of the sphere tracks which appear in the path of a beam of hard X-rays are almost certainly of the same nature as the fish tracks; they are merely of too small range to show any "tail."

Others, however, are plainly the tracks of electrons ejected by the K-radiations emitted by atoms from which an electron has been ejected by the primary beam. They may occur outside the primary beam; they are frequently situated close to the origins of other tracks, forming one component in several of the classes of paired β-ray tracks considered in the next section.

8. *Association of β-ray tracks in pairs or groups.*

The β-ray tracks produced in air exposed to X-rays very frequently occur in pairs or groups. The association in pairs or groups may be of any one of the following types:—

(1) A long-range track and a short-range track start from the same point.

(2) One, or sometimes two or more, short-range tracks, generally sphere tracks, appear close to the origin of a long-range track.

(3) Two short-range tracks form a pair without any long-range track being associated with them.

(4) Two long-range β-ray tracks, generally similar in range, have their origins near together.

(5) Two long range tracks start from the same point.

It is, of course, only when the tracks are not too closely packed that it becomes possible to distinguish some of the above types of pairing. Unless the average distance apart of the origins of the tracks exceeds considerably the distance apart of the components of a pair, the relationship of the members of a pair will not generally be obvious.

That the association in pairs or groups is real and not accidental is, I think, made sufficiently clear in the photographs which have been reproduced. Fig. 7, Plate 6, contains examples of types (1), (2) and (5).

Class (1). *A long-range track and a short-range track from the same point.* (Figs. 8, 9 and 17, Plates 7 and **11**.)

About 20 per cent. of the "long" β-ray tracks which have been produced by hard X-rays in air at pressures not differing much from atmospheric show distinct indications that a very short-range β-ray starts from the same origin. In some cases there is merely an enlarged head to the long β-track, no larger than some of the beads which occur along the course of the track; but very frequently the short-range track has a range of 2 or 3-tenths of a millimetre and shows quite distinctly as a lateral projection of the origin of the long track. At lower pressures the short tracks are of easily measurable length. In air at a pressure of 10 cm. of mercury many of these initial lateral tracks are from 1·5 to 2 mm. in length. A large proportion start approximately at right angles to the long track, but other very different angles, larger or smaller, occur. In several cases the short track is along the direction of the primary X-ray beam, like a "fish" track.

Even at the lower pressures a long-range track may show at its origin merely a bead (sometimes wholly or partially resolved into drops) to indicate the emission of the short-range β-ray. The effect of very short-range β-particles is more easily detected at low pressures, and it is probably mainly in consequence of this that a larger proportion of long tracks (about 30 per cent.) have at such pressure been recorded as showing the initial short-range track.

It is possible that in many cases the two particles have been ejected from the same atom, the β-particle which produces the short-range track having been ejected by the faster electron in the course of its escape. On the other hand the origin of this type of pairing of β-ray tracks may be essentially the same as that of the other types (classes 2, 3 and 4) in which the two β-particles do not come from the same atom.

Class (2). *A long-range track with short-range track close to its origin.* (Figs. 10, 11, 12 and 18, Plates 8, 9, and 11.)

When air is exposed to X-radiation of sufficiently short wave-length to produce β-rays exceeding about 15 mm. in range, about 30 per cent. of these have short tracks associated with them, but starting from separate origins; the origins of the long and short tracks are generally at distances varying from a small fraction of a millimetre up to several mm. in air at 50 mm. pressure. The long track of such a pair may or may not have a short track starting from its origin and forming with it a pair of the first class.

There can be little doubt that in some cases the short track of a pair of the second class is due to a β-particle, ejected from a second atom by the action of the K-radiation of the atom from which the faster β-particle was ejected. The K-radiations from oxygen or nitrogen would give rise to β-rays of ranges indistinguishable from these sphere tracks. There are frequently two, sometimes even three, or more, short tracks associated with a long one. Some cases of this kind may represent the handing-on of energy from atom to atom of successively lower atomic number; *e.g.*, the β-ray which gives rise to the long track may come from the K-level of an oxygen atom, which then emits its K-radiation; this may eject an electron from the K-level of a neighbouring nitrogen atom. The β-particle thus ejected from nitrogen would only have sufficient energy (about 100 volts $= O_K - N_K$) to set free a small group of ions; the nitrogen atom will in turn emit its K-radiation which may be absorbed in ejecting an outer electron from a neighbouring atom. The sphere tracks are as might be expected, on this view of different dimensions, and some of the smaller which have been resolved only contain about 10 pairs of ions.

The above explanation gives, however, by no means a complete account of the phenomena, and can in fact apply only to a relatively small number of cases of this type of pairing. In a narrow beam of soft X-rays only a small proportion, not exceeding two or three per cent. of the ordinary β-ray tracks are accompanied by sphere tracks (other than those which appear as beads on the β-ray tracks themselves); and such sphere tracks as do occur are as often as not outside the primary X-ray beam. The above explanation may apply in the case of these soft X-rays; the photographs show, however, that the greater number of the quanta of K-radiation emitted by the gas exposed to the primary beam must under these conditions either escape beyond the volume of air under observation before ejecting an electron and producing a sphere track or they are absorbed in the long β-ray tracks themselves.

With X-radiation of frequency sufficient to produce β-rays of 15 mm. or more in range, the proportion of those which have sphere tracks associated with them is greatly increased; the increase in the number of sphere tracks is confined almost entirely to the air lying within the primary X-ray beam. A sphere track outside the primary beam, like that in the lower part of Fig. 17, is quite rare. If the pressure is reduced they still remain within the primary X-ray beam while the average distance of each from its associated long-range track increases.

The effect of reducing the pressure shows that for the production of both the long and short components of a pair, the direct action of the primary beam is in general essential. This is also shown in a striking way when the X-ray beam is given the form of a narrow vertical sheet; the two components have then their origins very nearly in the same vertical plane.

If, as is probable, one of the components of a pair is primary and the other secondary, the secondary radiation from the point of origin of the primary β-ray is thus shown to be much more likely to eject a β-particle from an atom exposed to the primary X-rays than from one lying outside the primary beam.

The short track associated with the long one is not always a simple sphere track; its range may be sufficient to give it the comma-shaped or fish-like form. When of this form it is generally directed approximately along the direction of the X-ray beam in the same way as an independent "fish" track (figs. 12 and 18, Plates 9 and 11); it may, however, be directed with its "tail" pointing towards the origin of the longer track.

When the short track is of the simple sphere form, its most frequent situation relative to the origin of the long track is along a perpendicular to the initial direction of the long track (fig. 10, Plate 8).

When two short tracks are associated with a long track they may both be alike, and may form an obvious pair, or they may be quite unlike in range and orientation. The "long" track of fig. 12, Plate 9, has apparently two pairs of short tracks associated with it; one pair consists of two similar spheres, the other of a sphere track and a "fish" track.

Class (3). *Two separate short-range tracks.* (Figs. 13-16, Plates 9 and 10.)

Short-range tracks, other than those associated with the same long track also frequently occur in pairs. About 40 per cent. of such tracks belong to pairs.

Most frequently the pair takes the form of two sphere tracks. (Fig. 14, Plate 10.) A fish track is, however, frequently accompanied by a sphere track or by another fish track. (Figs. 15 and 13, Plates 10 and 9.)

There is a tendency for the points of origin of the two components of a pair to lie nearly on a line perpendicular to the axis of the X-ray beam. (Figs. 12 and 13, Plate 9.) One of the components—a sphere track—may lie outside the primary beam, but this is exceptional.

Experiments on the effects of varying the form and area of cross-section of the beam of X-radiation and the pressure of the air led to results similar to those which were found to hold for the previous class of pairs. If one of the components of the pair of β-rays is to be regarded as primary the other as due to radiation from the atom from which the primary β-particle has been ejected; then to explain the experimental results we must conclude that this secondary radiation is much more likely to eject a β-particle from an atom exposed to the primary radiation than from one lying outside the primary beam.

When the primary beam was a cylindrical pencil 0.5 mm. in diameter the average distance of the components of a pair was about 0·5 mm. in air at 50 cm. pressure. In a wide beam distances up to 5 or 6 mm. occurred, the mean distance exceeding 2 mm., and there was a much greater tendency for the two components of a pair to have their origins in a line nearly perpendicular to the axis of the X-ray beam; the frequency of occurrence of pairs as compared with single short-range tracks was also increased.

Class (4). *Two long-range tracks from neighbouring points.* (Figs. 21 and 22, Plate 12.)

A considerable proportion of the long tracks (*i.e.*, of all tracks other than sphere, comma and fish tracks) occur in pairs. In a wide beam of hard X-rays (of wave-length less than 0·5 A°) about 40 per cent. of such tracks were found to be paired. The proportion of paired tracks was smaller, not much exceeding 20 per cent. in a narrow beam of soft radiation in which all the tracks were less than about 7 mm. in range. In such a beam as has already been pointed out fish tracks are absent and sphere tracks few.

Both members of a pair are, with very rare exceptions, within the primary X-ray beam. In a wide beam their average distance apart amounts to

2 or 3 mm. in air at 50 cm. pressure. There is, as with pairs of the preceding class, a great tendency for the line joining the points of origins of the two members of a pair to be nearly perpendicular to the primary X-ray beam.

In a narrow beam, the average distance apart is diminished, as is to be expected if both components originate within the primary beam ; it is frequently about 0·5 mm. in a cylindrical beam of 0·5 mm. diameter. The line joining the origins of the two members of a pair is also in general much less inclined to the axis of the X-ray beam than in a wide beam.

At low pressures the average distance apart of the origins of the members of a pair is increased, and thus the two components of the only pairs which appear—since both rays in general start within the primary beam—have their origins in a line making only a small angle with the axis of the X-ray beam.

As with the two preceding classes of pairs, when the X-ray beam has the form of a narrow vertical sheet, the two members of a pair nearly always lie in almost the same vertical plane. This is perhaps the most striking proof that the direct action of the primary X-rays is involved in the production of both members of a pair.

Groups of three or even more long β-rays sometimes occur, but much less frequently than pairs. In a wide beam there is, as with a pair, tendency for all the members of such a group to have their points of origin in the same plane, nearly perpendicular to the primary beam.

Class (5). *Two long-range tracks from the same point.* (Figs. 19 and 20, Plate 11.)

The emission of two long-range β-rays from the same point (or from points too near for resolution in the stereoscopic pictures) is not uncommon. Cases of the emission of three and even of four β-rays from the same point have been noticed. These may all possibly form merely a particular case of the preceding class in which the two electrons have been ejected from molecules which are too near together for resolution. But in practice they form quite a distinct class. It seems, moreover, quite natural to suppose that, when the conditions for absorption are suitable, the radiation from an atom should have a specially great chance of being absorbed by the same atom or by another atom of the same molecule.

The number of cases of two long tracks originating from the same point as compared with the whole number of cases of paired long tracks is greatest in a narrow beam of X-rays traversing air at low pressure. Of the whole number of pairs of long tracks about one-third consist of two from the same point in a 0·5 mm. beam at a pressure of about 15 cm. This is in accordance with the view that the two components of the pair originate in the same molecule. For the chance of absorption by an atom of the same molecule as that in which the quantum of secondary radiation is emitted remains unaltered by lowering the pressure or narrowing the beam, while the total number of other molecules available for absorption is proportional to both the air pressure and the cross section of the beam.

There is a tendency for the two members of a pair of long β-rays, whether they originate at the same or neighbouring points, to be similar in range, and in the angles which their initial directions make with the axis of the primary beam of X-rays. A striking example is that of fig. 22, Plate 12.

Two long tracks from the same or neighbouring points may be accompanied by associated short tracks. For example, in fig. 20, Plate 11, a typical "comma" track is associated with two long tracks and another short track, the last three apparently starting from the same point.

9. *Time interval between the ejections of the two components of a pair.*

Owing to the fact that a resistance was inserted in the circuit, each discharge of the Leyden jars through the X-ray bulb lasted an appreciable time—about 0·01 second. During this time the nature of the X-rays emitted may have varied much in wave-length, polarisation and otherwise. Thus the tendency of the two β-ray tracks of a pair to be similar might be interpreted as meaning that the β-particles were ejected so nearly simultaneously that the radiations effective in the ejection of both were similar in character. Some of the photographs were taken under conditions such that the expansion occurred during the X-ray discharge, so that, while some of the tracks were sharp, others (due to β-particles ejected before the expansion was completed) were wholly or partially separated by the electric field into positive and negative diffuse tracks. In such a picture, in accordance with the above explanation, a pair may occur in which both components are sharp, while nearly all the other tracks are diffuse, or diffuse when most of the other tracks are sharp.

What is somewhat unexpected is the appearance in such pictures of what seem undoubtedly to be pairs, in which one component is sharp and the other diffuse; *i.e.*, pairs of which the two components have been ejected with an appreciable time interval. A rough estimate can be made from the vertical separation which the positive and negative ions of the diffuse tracks suffered before being fixed; it is of the order of 1/1,000 of a second.

10. *On the origin of the paired tracks.*

In Section 5 evidence was brought forward to show that X-rays of sufficiently short wave-length in traversing air cause the ejection of two classes of β-particles which differ greatly in range; the difference in their kinetic energies generally corresponds to more than 20,000 volts. Let us suppose that as a result of ejection of the electron and consequent re-arrangement of the remaining electrons there follows in both cases the emission of a quantum of K-radiation from the atom.

The K-radiation from an atom of nitrogen in the absence of other influences is not able to eject an electron from the K-level of a second atom of nitrogen. The phenomena relating to the paired tracks suggest that such an atom, when exposed to the K-radiation from a similar atom, together with radiation of higher frequency, is able to absorb both radiations (with ejection of a K electron) much more readily than either separately. Let us suppose that the ejection of the electron by the primary X-rays, whether it occurs with or without the help of the K-radiation, may be either of the type which gives the long-range β-particle or of that which gives the short-range forward-directed β-particle. Then all the various types of pairs—all possible combinations of long and short β-ray tracks—may be accounted for.

In the case of an element of low atomic number like nitrogen, it is perhaps not impossible that the K-radiation, while not able of itself to eject an electron from the K-level of a similar atom, may be absorbed in transferring the electron to an outer level, and that the K-radiation may be then re-emitted and handed on from atom to atom like ordinary resonance radiation. The occasional occurrence of a time interval of the order of 1/1,000 of a second between the ejection of the primary and secondary β-particles is perhaps more easily understood on this view.

Summary of Results.

Many hundred stereoscopic pictures showing the number, distribution, direction of ejection and range of the β-particles emitted from atoms in air exposed to X-rays have been obtained and examined. The following are some of the conclusions to which a study of the photographs has led.

(1) The cloud-method is able to deal with individual quanta of radiation, in the sense that the track of the electron ejected from the atom which emits the quantum of radiation and that of the electron ejected from the atom which absorbs the radiation may under suitable conditions be identified.

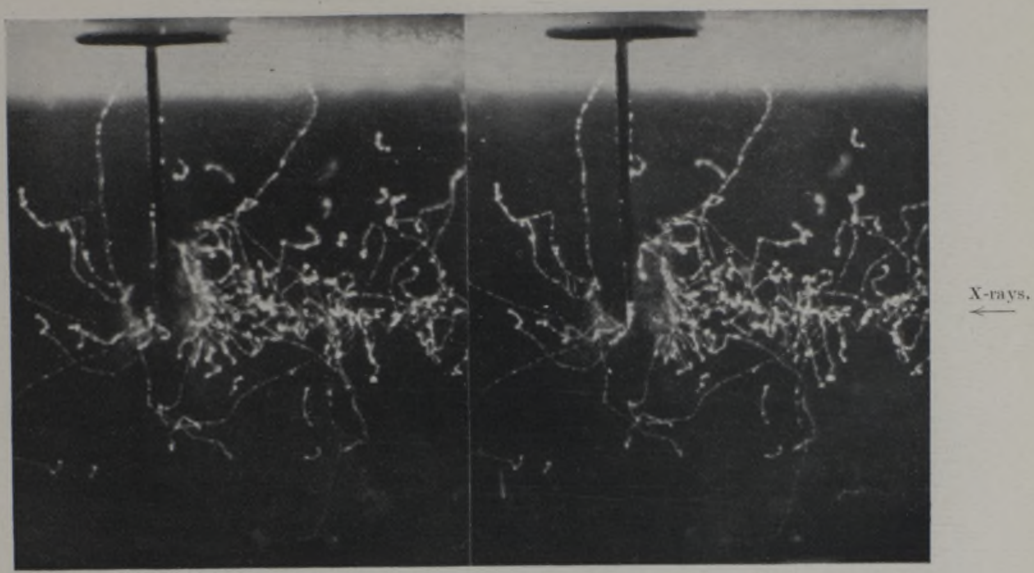
(2) Two classes of β-ray tracks are produced in air by the primary action of X-radiation of wave-length less than about 0·5 A°—(*a*) those of ejected electrons with initial kinetic energy comparable to a quantum of the incident radiation, and (*b*) tracks of very short range. The short range electrons are ejected nearly along the direction of the primary X-rays. Their direction and range and the value of the minimum frequency of the radiation which is required to produce them are in agreement with the suggestion made by A. H. Compton, that a single electron may be effective in scattering a quantum of radiation and that in so doing it receives the whole momentum of the quantum. The short-range tracks are probably related to the phenomena which have led to the postulation of a "J"-radiation.

(3) The ordinary long-range tracks may be divided into three classes according to the direction of ejection of the electron. The majority have a large forward component comparable with the lateral component; a considerable proportion, of the order of 20 per cent., are ejected almost exactly at right angles to the primary X-ray beam; others have a large backward component.

(4) Partial polarisation of the primary beams is indicated by the direction of ejection of a number of the β-particles being in one plane—that containing the direction of the cathode rays in the X-ray tube.

(5) β-rays in air exposed to X-rays frequently occur in pairs or groups, of which five classes have been distinguished. The pairs probably consist of one K-electron ejected by the direct action of the primary X-rays, and of a second electron ejected by the combined action of primary radiation and of the K-radiation from the atom from which the first electron was ejected.

Fig. 1 (×2).



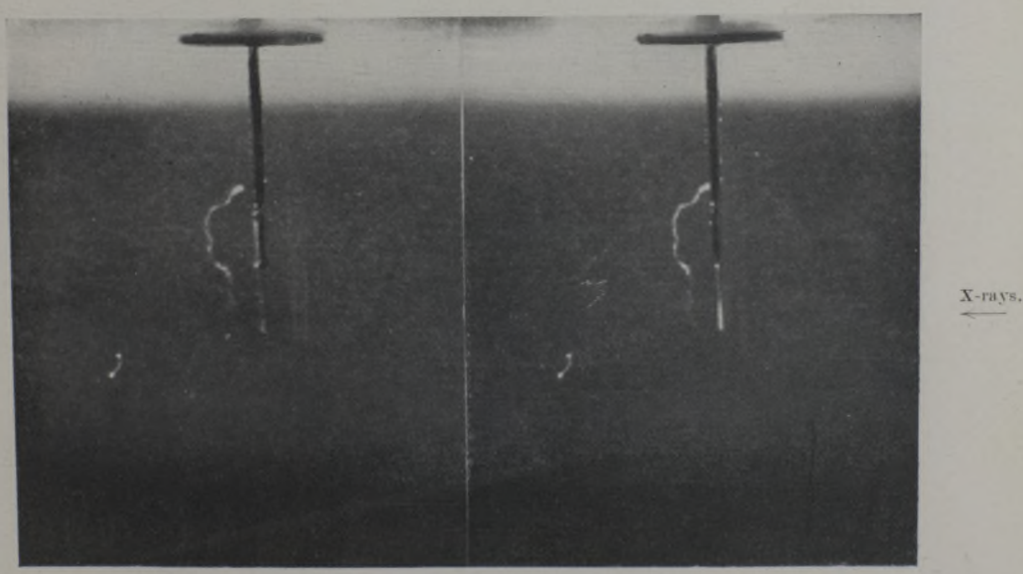


Fig. 2 (×2).

Experiments with copper target (Section 4). Diameter of cylindrical X-ray beam 0·5 mm. Thickness of copper plate 8×10^{-3} cm. Final air density about 0·7 normal. In (2) aluminium screen, 9·2 mm. thick, was interposed.

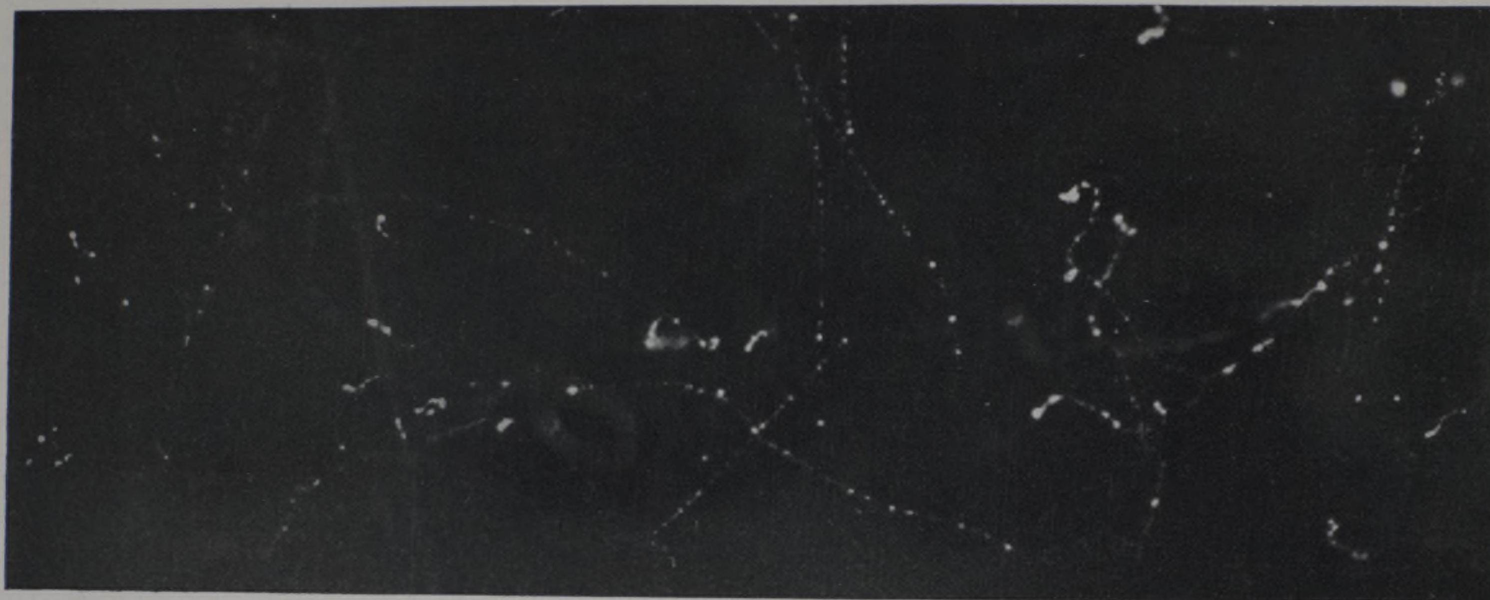


FIG. 3 (×3).

Effects of hard X-rays: (1) production of long-range and short-range β tracks, (2) forward direction of the "fish" tracks, (3) long tracks at right angles to X-rays, others with large forward component.
X-ray beam 15 × 4 mm. in section, filtered through 14 mm. of aluminium.
Final air pressure 20 cm.

Wilson.

Roy. Soc. Proc., A, vol. 104, Pl. 3.

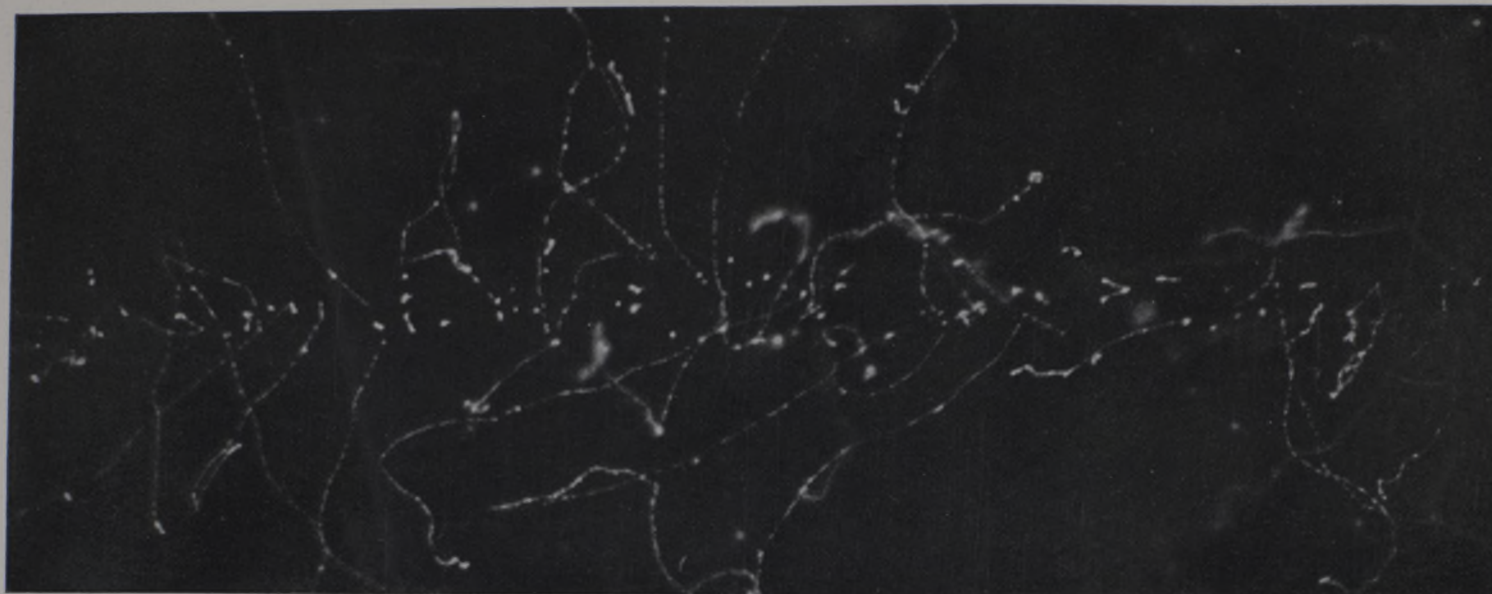


FIG. 4 (×3).

Different classes of β-ray tracks, "long," "fish," and "comma" tracks produced by hard X-rays. Initial forward component in long tracks. X-ray beam, about 3 mm. in diameter, had traversed 6×10^{-3} cm. lead.
Final air pressure 50 cm.

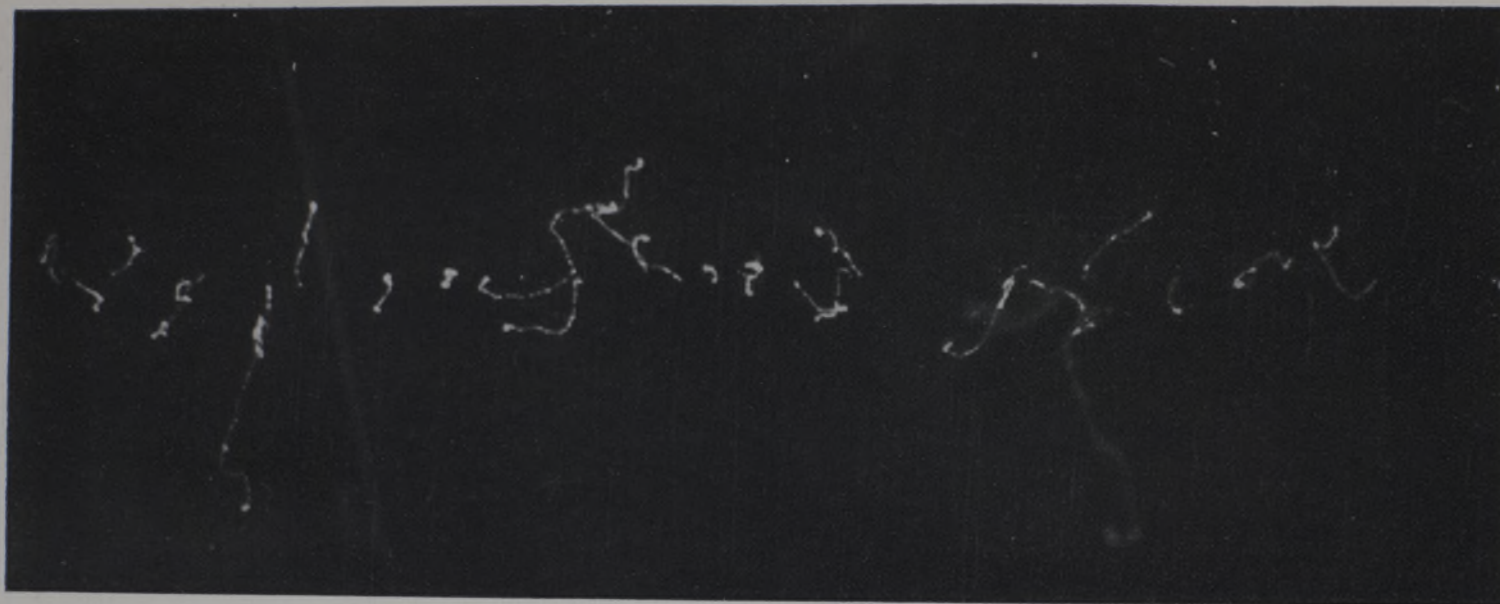


FIG. 5 (×3).

Narrow cylindrical beam of soft X-rays. Sphere tracks and fish tracks absent. Diameter of X-ray beam 0·5 mm. Final pressure 50 cm.

Roy. Soc. Proc., A, vol. 104, Pl. 5.

Fig. 6 (×3).

Long tracks with large forward component. Sphere tracks. Cylindrical X-ray beam, 0·5 mm. in diameter, has traversed 8×10^{-3} cm. copper. Final pressure 19 cm.

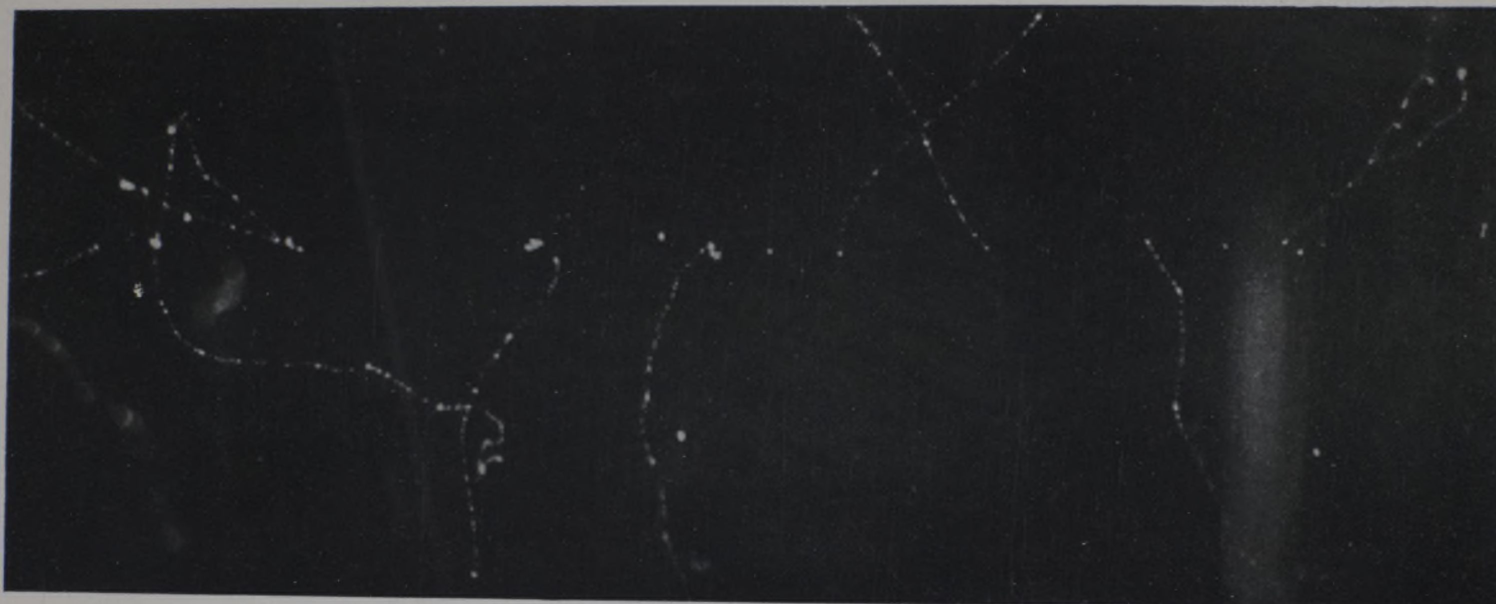
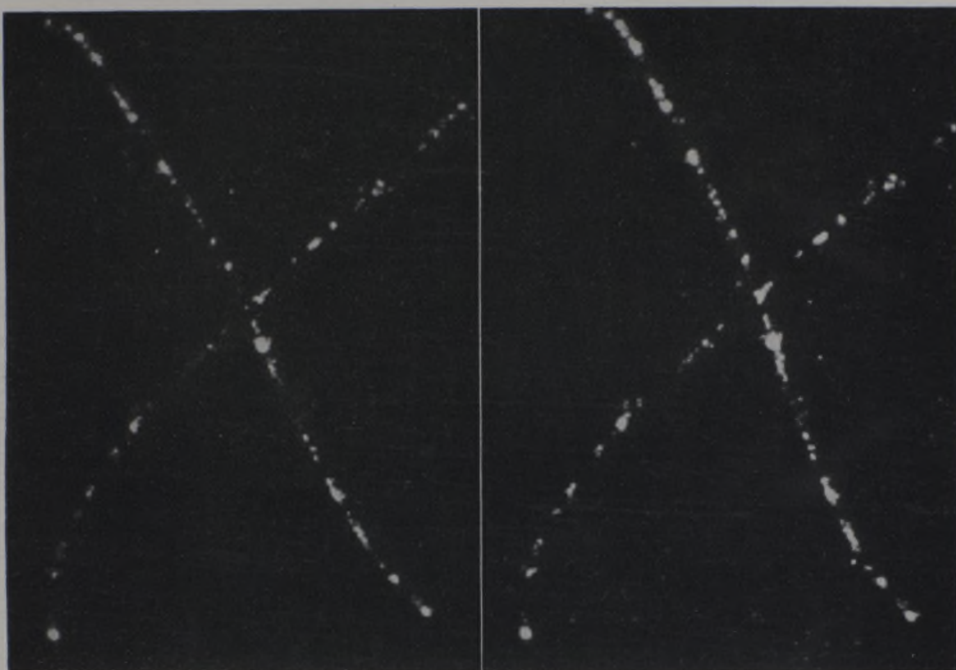


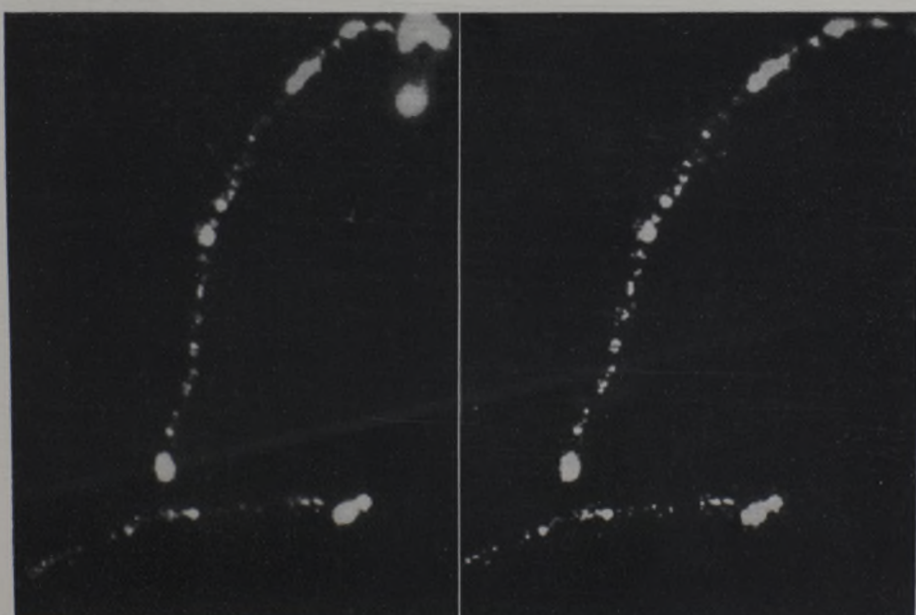
FIG. 7 (×3).

Different types of pairs. The branched track on the right has a sphere at its origin and another near it. At the left of the picture two long tracks start from the same point. Other long tracks have sphere tracks associated with them. One long track has large initial backward component. Cylindrical X-ray beam, 0·5 mm. in diameter, had traversed 2·9 mm. aluminium. Final air pressure 20 cm.

Fig. 8 (×8).



X-rays. ←



X-rays. ←

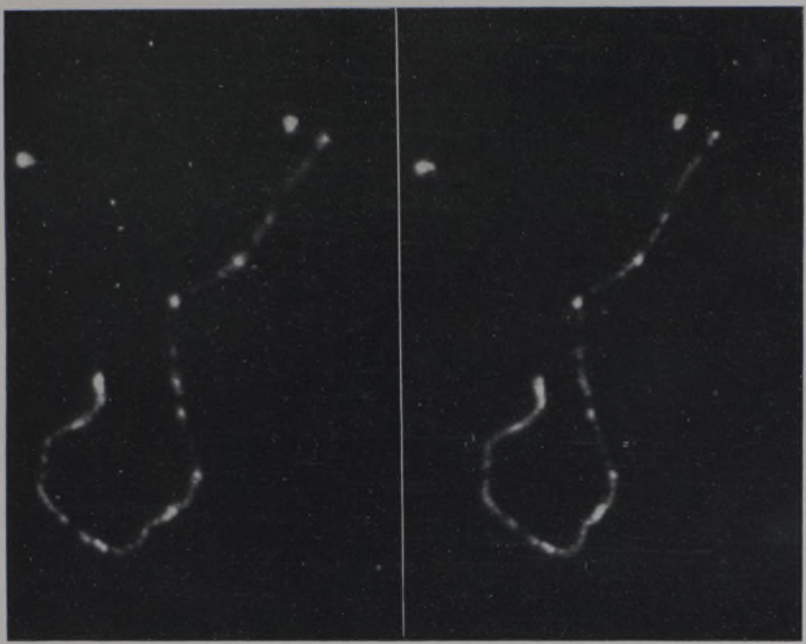
Fig. 9 (×8).

Paired tracks of type 1 (Section 8).

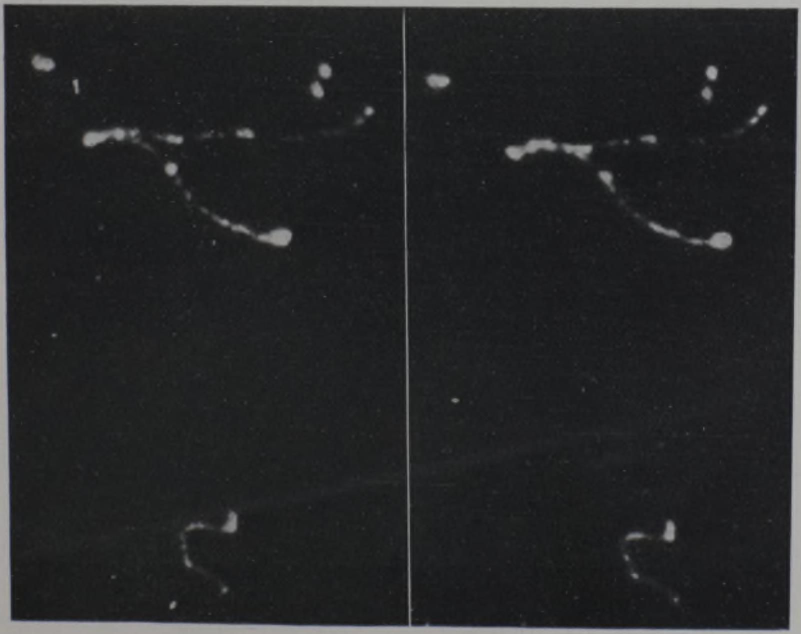
Fig. 8.—Two long tracks from Fig. 7.

Fig. 9.—Final air pressure 19 cm.

FIG. 10 (×8).



← X-rays.

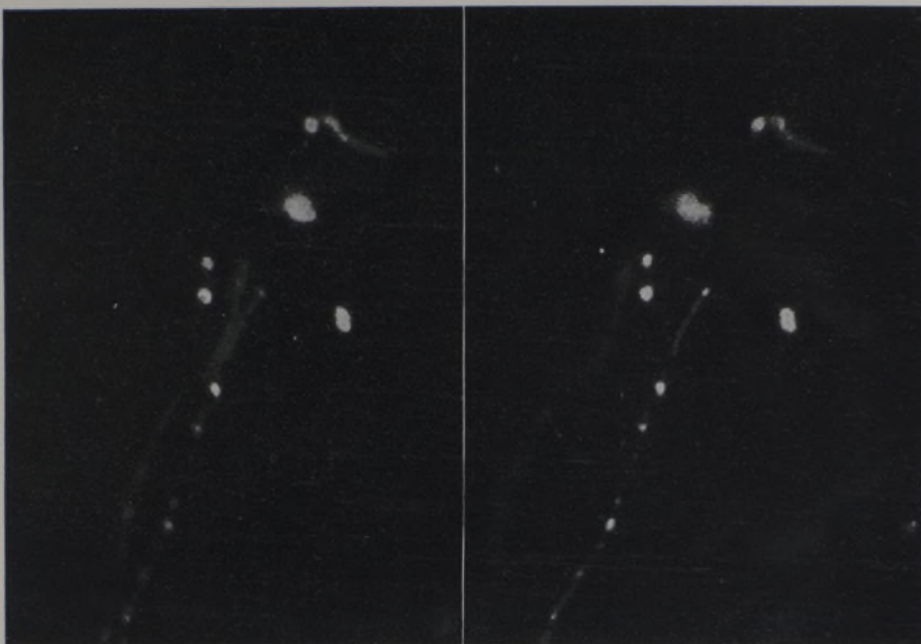


← X-rays.

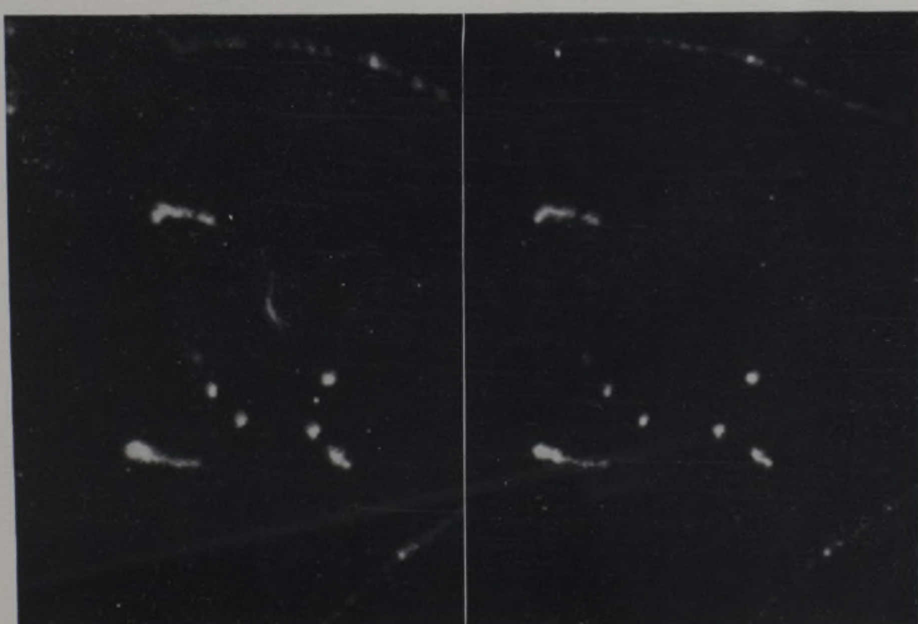
FIG. 11 (×8).

Paired tracks of type 2 (Section 8).
Final pressure 53 cm.

FIG. 12 (×8).



X-rays.



X-rays.

FIG. 13 (×8).

FIG. 12.—Long track with associated short tracks. Final pressure 50 cm.
FIG. 13.—Paired fish tracks and group of sphere tracks. Final pressure 50 cm.

FIG. 14 (×8).

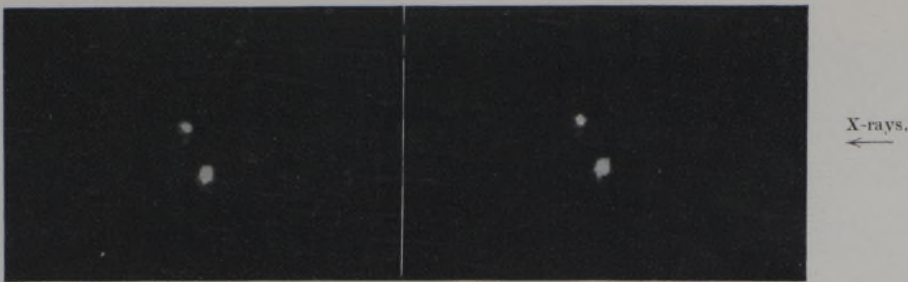


FIG. 15 (×4).

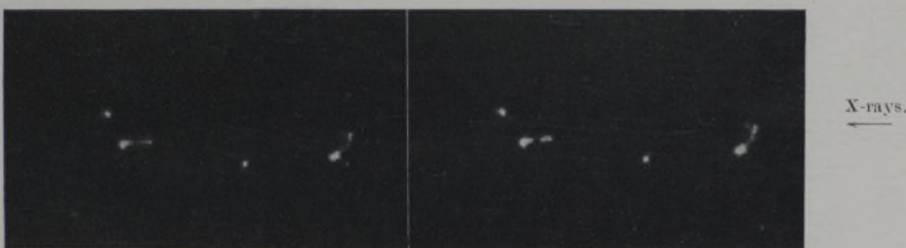


FIG. 16 (×4).

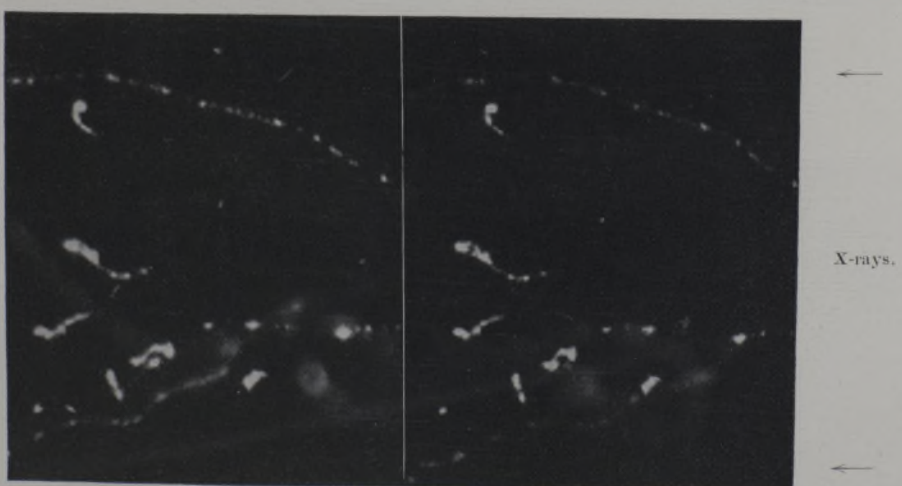


FIG. 14.—Paired sphere tracks. Final pressure 20 cm.

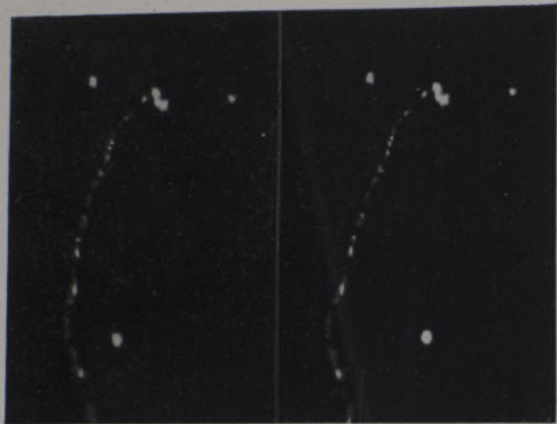
FIG. 15.—Fish track and associated sphere track. Final pressure 19 cm.

FIG. 16.—Associated fish tracks (from Fig. 3).

Wilson.

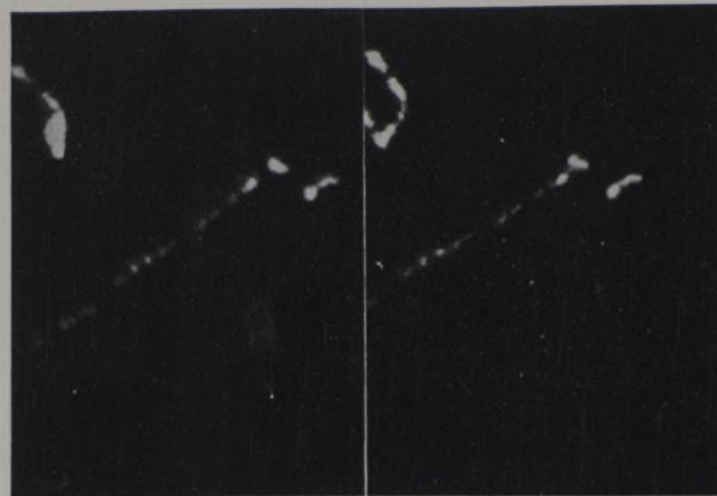
Roy. Soc. Proc., A, vol. 104, Pl. 11.

FIG. 17 (×4).

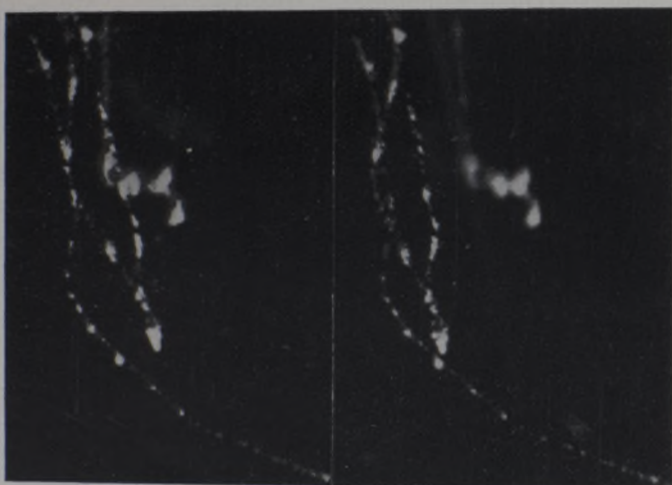


X-rays.

FIG. 18 (×4).

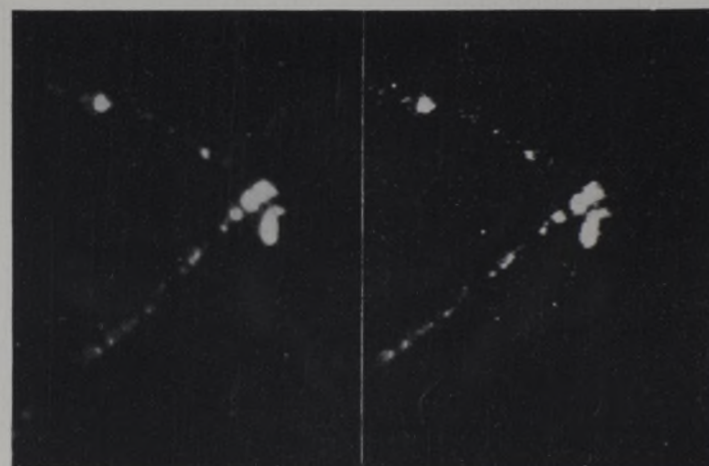


X-rays.



X-rays.

FIG. 19 (×4).



X-rays.

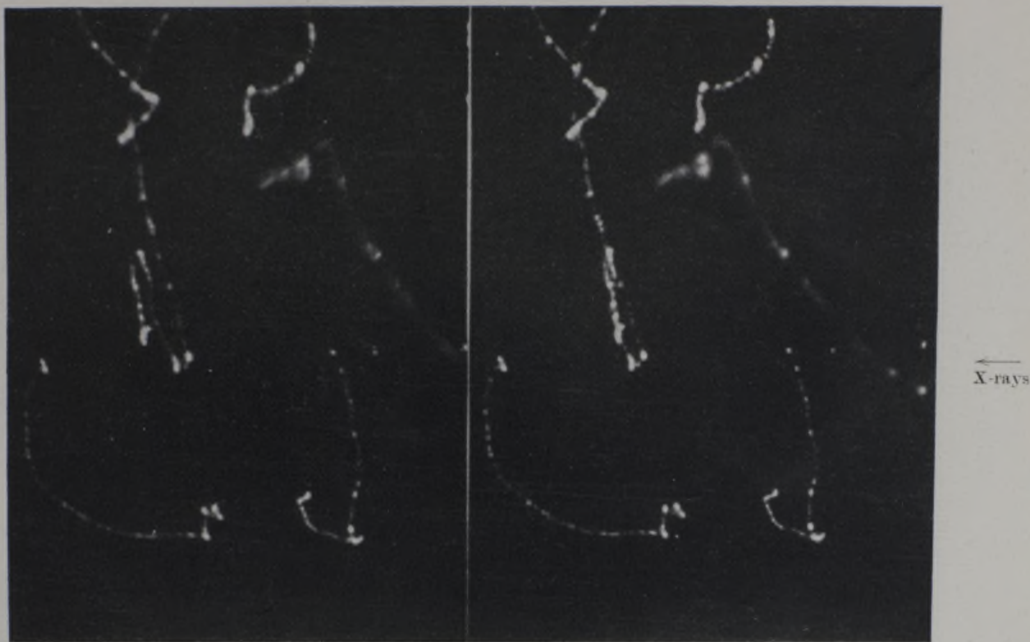
FIG. 20 (×8).

Associated Tracks.

FIGS. 17, 19, 20.—Final pressure 20 cm.

FIG. 18.—Final pressure 50 cm.

Fig. 21 (×4).



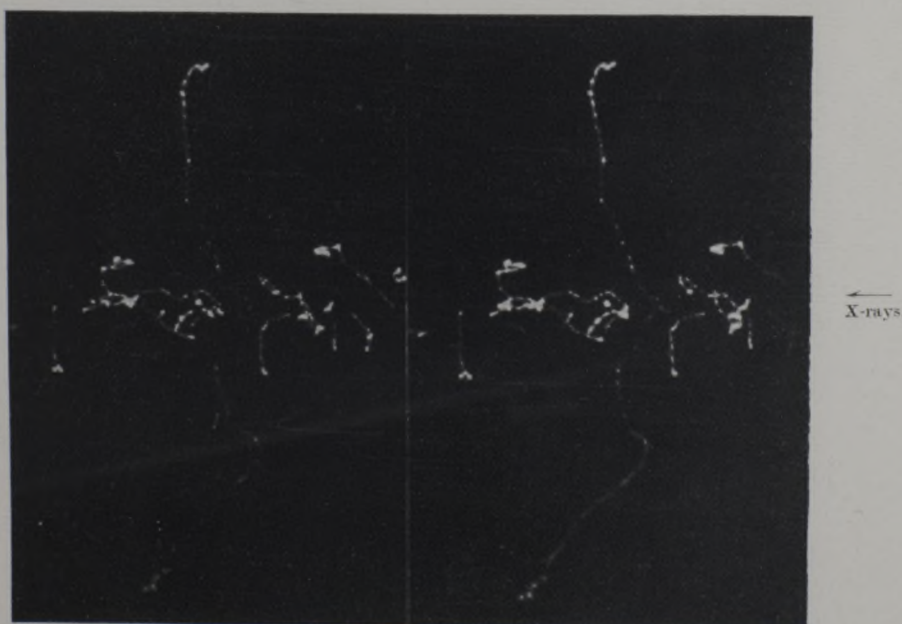


Fig. 22 (×4).

Paired long tracks (Section 8).

Fig. 21.—Final pressure 55 cm.

Fig. 22.—Final pressure 50 cm.

Investigation on X-Rays and β-Rays by the Cloud Method. Part II.—β-Rays.

By C. T. R. Wilson, F.R.S.

(From the Solar Physics Observatory, Cambridge.)

(Received June 23, 1923.)

[Plates 16–24.]

The greater part of the material used in the study of the β-ray tracks was obtained during the experiments with X-rays described in Part I. A number of photographs were also taken of the tracks of fast β-particles emitted by radio-active substances or ejected from the walls of the cloud chamber by γ-rays. Some photographs of α-ray tracks were obtained during the course of these experiments; these have been published elsewhere.*

1. *General Character of β-ray Tracks.*

The tracks of the fastest β-ray particles in air are generally perfectly straight over distances of many centimetres. Within the last 10 cms. of its range the deviations in the path of a β-ray are very marked and become more and more so as the velocity of the particle diminishes. Fig. 1 (Plate 16) shows in a striking way the contrast between the paths of fast and slow β-particles.

The deviations are of three types:—

(1) A gradual bending due to an accumulation of small deviations; (2) a sudden deviation due to a close encounter with an electron which is in consequence ejected with sufficient velocity to form a branch track; and (3) a sudden bend due to the passage of a β-particle close to the nucleus of an atom; this is generally unaccompanied by any branch track and the deviation is generally through a large angle, not infrequently approaching 180°. Figs. 2, 3, 10, 11, 12 illustrate the different kinds of deviation in the last few centimetres of the path.

The increase in the ionisation as the velocity of the β-particle diminishes is well shown by the increasing density of the cloud track as the end of range is approached.

2. *Range and Velocity.*

I have not thus far attempted to make accurate measurements of the ranges of β-particles of known velocity. The measurements, already described in

* 'Proc. Camb. Phil. Soc.,' vol. 31, p. 405 (1923).

Part I, Section 4, of the ranges of β-particles due to characteristic radiations from metals show that from ranges between 0·2 mm. and 1·5 cm. Whiddington's law* holds approximately; and the range is proportional to the square of the kinetic energy. To give a range of 1 cm. the energy of the β-particle has to be the equivalent of about 21,000 volts. The range is measured along the track in the three-dimensional picture and reduced to normal pressure. The comparative ranges of the β-particles due to the K-radiations of copper and silver are shown in figs. 4 and 5.

The fourth-power law connecting range and velocity is in accordance with Sir J. J. Thomson's theory† of ionisation by β-particles. The range of a β-particle of given initial velocity depends on the rate at which it loses energy along its path as a result of collisions. Some variation in the ranges of β-particles of given length are therefore to be expected; for example, a particle may meet with more than the average number of collisions in which a large amount of energy is transferred to ejected electrons, and may thus have an abnormally short range. An extreme case is that of a β-ray track with a visible branch; such a track is in general of considerably less than the average range. It was found, however, that the initial kinetic energy of a β-particle which produced a branched track could generally be obtained with considerable accuracy from measurements made on the track. To do this the energies of the primary and secondary β-particles immediately after the encounter were deduced from their ranges; the two branches could then be replaced by a single track of range corresponding to the sum of these energies. The equivalent range of the whole track as thus completed was generally found to be in quite good agreement with that of the unbranched tracks when approximately homogeneous radiation was used.

3. *Ionisation along the Path of a β-ray.*

Among the photographs of β-ray tracks obtained in 1912‡ were some in which the cloud tracks were resolved into droplets, and in which, in addition to single pairs of ions, groups containing several pairs appeared along the track. The occurrence of these groups was taken as indicating that in many cases an electron is ejected from an atom by the action of the β-particles with sufficient velocity to produce other ions by collision—secondary ionisation. This interpretation has been confirmed by the more recent work; the largest groups are

* 'Roy. Soc. Proc.,' A, vol. 86, p. 360 (1912).

† 'Phil. Mag.,' vol. 23, p. 449 (1912).

‡ 'Roy. Soc. Proc.,' A, vol. 87, p. 277.

indistinguishable from very short branch tracks. The number and distribution of the ions along the path of a β-particle have been found to be in general accordance with the theory introduced by Sir J. J. Thomson* and developed by Bohr† and others.

Depending upon the conditions of the experiment (pressure, expansion, ratio, timing of the various events and magnitude of the electric field) different degrees of sharpness or diffuseness of the cloud tracks formed by condensation on the ions may result. It is assumed that the illumination and focussing are sufficiently good to give a sharp image of any isolated cloud particle; these are generally small enough to act virtually as point sources of light. The diffuseness of the tracks then depends on the extent to which the ions have been dispersed by the action of the electric field and by diffusion and mutual repulsion before being fixed by condensation of water.

There are three cases which are specially suitable for studying different aspects of the problem of the ionisation along the path of the β-particle.

To determine the number of groups per cm. of the tracks—*i.e.*, the primary ionisation, or number of atoms from which the original β-particle ejects an electron—each track must be sufficiently sharp to prevent confusion of successive groups (fig. 7, Plate 19).

To obtain the total ionisation, primary and secondary, the ions must be separated sufficiently to ensure that each gives an easily resolvable cloud particle; the electric field must be strong enough to ensure separation of the positive and negative ions of each pair. The conditions may be made such that the positive and negative ions form separate diffuse tracks, as happens when the β-particle passes through the gas before the expansion (fig. 9); but separation of the positive and negative tracks is not essential (fig. 8).

The most interesting case is the intermediate one, in which not only are the individual groups readily distinguished, but each group is resolvable into its component drops; so that both the number and distribution of the ions produced by the β-particle are obtained. In this case both the number of electrons ejected from atoms of the gas by the primary β-particle (along a limited portion of its path) and the number of ions produced by each electron thus ejected are recorded in the photograph (fig. 6).

Results.—The primary ionisation—given by the number of groups per cm. along the β-ray track—is more easily measured than the total ionisation per

* J. J. Thomson, *loc. cit.*

† N. Bohr, 'Phil. Mag.,' vol. 30, p. 581 (1915); S. Rosseland, 'Phil. Mag.,' vol. 45, p. 65 (1923).

centimetre; this is fortunate, as it is with the primary ionisation that theories of ionisation along the path of a β-particle more directly deal.

Most of the measurements have been made on the initial portions of the tracks of β-rays excited in air by X-rays. Counts were made of the groups per cm. in 46 such tracks and included considerably more than 1,000 groups.

The tracks were all formed in air at pressures below 20 cms. of mercury, and the groups (including single pairs) in the initial one or two cms. of the tracks were counted. The number per cm. at atmospheric pressure was deduced on the assumption that the ionisation is proportional to the pressure.

These measurements gave for the primary ionisation (number of groups per cm.) a mean of 96 per cm. at a distance of about 1·5 cm. from the end of the β-ray track in air at atmospheric pressure. Numbers equal to 104 groups per cm. and 83 groups per cm. were obtained for the primary ionisation at about 1 cm. and 2 cms. from the end of the range respectively; but only a small number of observations were available for these portions of the range.

The velocity of the β-particle at 1·5 cm. from the end of its range was deduced from measurements of the range of β-particles of known velocity. (See Part I, Section 4.)

The velocity of the β-particles at 1·5 cm. from the end of its range is found in this way to be $9 \cdot 5 \times 10^9$ cms. per sec., corresponding to about 25,000 volts; it is for a velocity of approximately this magnitude that the value of 96 per cm. found for the primary ionisation by the β-particle applies. According to Thomson's theory the ionisation per cm. should vary inversely as the square of the velocity of the β-particle; the values found for the ionisations at 1, 1·5 and 2 cms. from the end of the range are in approximate agreement with this relation. The velocity $9 \cdot 5 \times 10^9$ differs so little from 10^{10} cms. per second that we may safely deduce the primary ionisation at the latter velocity, on the assumption that the ionisation varies inversely as the square of the velocity.

The primary ionisation due to a β-particle having a velocity of 10^{10} cms. per second is about 90 per cm. in air at 760 mm. and 20° C.; *i.e.* it ejects an electron from about 90 atoms per cm. of its path.

Sir J. J. Thomson obtained the expression $I = \frac{2\pi N n e^4}{m_0 u^2 W}$ for the primary ionisation per cm. along the path of a β-ray, N being the number of molecules per c.c., n the number of effective electrons per molecule, m_0 the mass of the electron, e the electronic charge, u the velocity of the β-particle, and W the work required to remove an electron from the molecule; it is assumed that m_0u^2 is large in comparison with W. If we make use of the results now obtained for the primary ionisation in air ($I = 96$, when $u = 9 \cdot 5 \times 10^9$) and put $n = 10$ the number of electrons, other than those of the K-level, in the nitrogen molecule, we obtain for W the value $6 \cdot 8e/300$; *i.e.*, to remove an electron from the molecule the potential required is 6·8 volts. This is less than half the ionising potential as given by recent work, and is very near the "resonance" potential, 7·5 volts. There may be an error of 10 per cent. in the determination of u^2 and therefore of W; experimental error cannot account for the large difference between W and the ionisation potential.

The tracks of nine fast β-particles from Radium and Thorium and their products, and one from an unknown source (it appeared in a picture of the tracks of β-particles due to X-rays), were also found to be suitable for direct determination of the primary ionisation. All these tracks were almost perfectly straight. The air pressure varied between 18 and 50 mm. of mercury.

The primary ionisation in the paths of these fast β particles amounted in all cases, when reduced to atmospheric pressure, to between 18 and 22, the mean being 20 per cm. If we assume the primary ionisation to vary inversely as the square of the velocity (in accordance with Thomson's theory and with W. Wilson's measurements in the ionisation by very fast β-rays) we deduce from the primary ionisation as the mean velocity of these fast β-particles, $2 \cdot 1 \times 10^{10}$ cm. per second.

It would obviously be of interest to have direct determinations of the primary ionisation due to fast β-rays of known velocity. The only method available for determining the velocity of the particles which produced the tracks used in the above measurements of the primary ionisation depended on the existence of branch tracks. Several tracks of fast β-particles had such branches, and in one case at least the conditions admitted of a fairly definite measurement. From the range of the branch track the velocity of the ejected electron was obtained, while the angle through which the β-particle was deflected by the encounter gave a measure of the ratio of the momenta of the ejected electron and the deflected β-particle.

While no great accuracy could be claimed for the measurement it was sufficient to show that the velocity of the β-particle exceeded 2×10^{10} cms. per sec. The primary ionisation found for this track was 23 per cm.

These observations on fast β-rays point to the conclusion that the primary ionisation continues to vary approximately as the inverse square of the velocity of the β-particle up to velocities as great as two-thirds of that of light.

As already mentioned, a few photographs have been obtained in which not only is the cloud track, which has been formed by the passage of a β-particle, resolvable into its component groups (each indicating the expulsion of an electron from an atom by the original β-ray) but each group is resolved into its component droplets. Each droplet represents a single ion.

Eight β-rays produced by X-rays have furnished tracks of which considerable portions showed this double resolution. The total number of groups in the resolved portions of these tracks was 128. Of these 55 consisted of single pairs of ions, there were 29 groups of four ions, 16 of six, 13 of eight, and 16 groups of more than eight ions.

One of the fast β-ray tracks which was resolved into groups—one described above as from an unknown source—also had its groups themselves resolved into drops (fig. 6). Out of 24 groups there were 13 pairs, 5 fours, 2 sixes, 2 eights, 1 ten and one unresolved larger group.

The fact that the single pair is the commonest kind of group, and that the frequency of occurrence continually diminishes as the number of ions in the group increases, is in accordance with the Thomson-Bohr theory.

The measurement of the total ionisation (primary + secondary) per cm. of a β-ray track is subject to the following difficulty. Comparatively large groups of ions (set free by electrons which have been ejected with considerable velocity) occur at intervals along the track, and the ionisation found per cm. is very different according as the portion of the track in which we make the count is made to include such a group or to stop short of it. The total ionisation per cm. of a β-ray track is in a sense essentially indeterminate and the above practical difficulty is merely an illustration of this fact. In an extreme case the ejected electron or secondary β-particle may have such a velocity that it forms a well defined branch to the primary track; in this case it would plainly be absurd to include the total ionisation produced by the secondary β-ray in the ionisation per unit length of the primary β-ray track. And the matter is not essentially different when the secondary β-ray has too small a velocity to form a recognisable branch track. The total ionisation due to a β-ray (as distinct from the ionisation per cm.) is free from this ambiguity, since the ionisation produced by all its secondary β-rays, including visible branches, is obviously to be included.

The ratio of the whole ionisation per cm. to the primary ionisation, obtained by dividing half the total number of drops in the above double resolvable tracks by the number of resolved groups amounts to 1·9. For the fast β-ray track the ratio is 1·8. We undoubtedly get in this way too low a value for the mean ratio of total ionisation per cm. to primary ionisation per cm., because only smaller groups are included, these being the only ones which can be resolved.

The ionisation per cm. (primary + secondary) was also determined in the case of six diffuse tracks of range about 1·5 cm., in which the groups were too diffuse to be separated from one another. The mean number of pairs of ions per cm. (at atmospheric pressure) was 337, *i.e.*, 3·5 times the value found, in the same region of the β-ray track, for the primary ionisation; but the number per cm. of the different tracks varied between 272 and 416. This large variation is not surprising in view of the difficulty to which reference was made above. To illustrate this difficulty it may be mentioned that one resolved group on the track of a fast β-ray, which was divided into completely separated positive and negative components, showed about 75 droplets in the positive and an equal number in the negative cloud.

While the value found for the whole ionisation per cm. is much more uncertain than that found for the primary ionisation alone, it may be taken as between 3 and 4 times the primary when the range of the β-particle is about 1·5 cm., *i.e.*, when its velocity is about 10^{10} cms. per sec.

It is of interest to calculate the energy given, according to Thomson's theory, by the β-particle to electrons ejected from the atoms per cm. of its path; and to compare this, on the one hand, with the total energy lost per cm. (known from the relation between ranges and voltages), and, on the other, with the energy equivalent of the secondary ionisations due to the ejected electrons.

The number of cases per cm. of the path of a β-particle in which it gives to an electron energy exceeding a given value W is

$$\mathrm{I} = \frac{\pi e^4 \mathrm{N} n}{\mathrm{T}} \left(\frac{1}{\mathrm{W}} - \frac{1}{\mathrm{T}}\right) \text{ where } \mathrm{T} = \tfrac{1}{2} m_0 u^2.$$

Thus
$$\frac{d\mathrm{I}}{d\mathrm{W}} = -\frac{\pi e^4 \mathrm{N} n}{\mathrm{T}\mathrm{W}^2}.$$

The energy transferred per cm. of its path by the β-particle to the electrons is

$$-\frac{d\mathrm{E}}{dx} = \int \mathrm{W}\, d\mathrm{I} = \frac{\pi e^4 \mathrm{N} n}{\mathrm{T}} \int \frac{d\mathrm{W}}{\mathrm{W}}$$

$$= \frac{\pi e^4 \mathrm{N} n}{\mathrm{T}} \log_e \frac{\mathrm{W}_2}{\mathrm{W}_1},$$

where W_1 is the energy required to get an electron out of the atom, and W_2 may be taken to be the energy which an ejected electron must acquire to produce a just recognisable branch track. (The arbitrariness of the upper limit of W corresponds exactly to the practical difficulty in the measurement of the total ionisation per cm. to which reference was made above.) It is assumed that the velocity of the β-particle is small enough to allow the change of effective mass with velocity to be ignored.

If there are two classes of electrons in the molecule (*e.g.*, outer electrons and K-electrons) requiring different energies W_1 W_k to eject them, then

$$-\frac{dE}{dx} = \frac{\pi e^4 N}{T}\left(n_1 \log\frac{W_2}{W_1} + n_2 \log\frac{W_2}{W_k}\right).$$

The energy W_2 required to enable an ejected electron to produce a visible branch is in the neighbourhood of 1,500 volts; while W_1 is about 10 volts. The ratio W_2/W_1 is about 150; even if we take W_2/W_1 as 200 instead of 150 we only alter $\log W_2/W_1$ by about 5 per cent. It is thus unnecessary to know with accuracy the limits W_2 W_1.

If we insert the known values of the constants in the above equation we have for the case of nitrogen (which will give very nearly the same result as air), at 760 cm. and 20° C., the loss of energy of the β-particle in volts,

$$-\frac{dV}{dx} = \frac{9 \times 10^7}{V} \text{ volts per cm.}$$

This is the calculated loss of voltage by the β-particle per cm. due to energy transferred to the ejected electrons. The actual total loss of volts per cm. is known from the experimentally determined relation between the range and kinetic energy of the β-particle, expressed in volts,

$$V = 21000\, R^{\frac{1}{2}}$$

and is equal to $\frac{2 \cdot 2 \times 10^8}{V}$ volts.

Rather less than half the total loss of energy of the β-particle is accounted for by the energy which, according to Thomson's theory, is given to the ejected electrons.

The ionisation when V is about 25,000 volts is (according to the rather scanty data available) about 340 pairs per cm.; of the 340 negative ions about 95 represent the electrons ejected by the primary β-ray. The calculated energy given to these electrons by the primary β-particle is $9 \times 10^7/(2 \cdot 5 \times 10^4) = 3 \cdot 5 \times 10^3$ volts, *i.e.*, $3 \cdot 5 \times 10^3/95 = 37$ volts per electron ejected by the primary β-particle, or about $3 \cdot 5 \times 10^3/340 = 10$ volts per pair of ions (primary and secondary) produced. The total energy actually lost per cm. by a β-particle when its energy corresponds to about 25,000 volts is approximately $2 \cdot 2 \times 10^8/2 \cdot 5 \times 10^4$ = about $8 \cdot 8 \times 10^3$ volts, *i.e.*, about $8 \cdot 8 \times 10^3/95 = 93$ volts per electron ejected, or $8 \cdot 8 \times 10^3/340 = 26$ volts per pair of ions produced.

A part of the energy of the primary β-particle which is not used in ejecting electrons is spent in exciting radiation in the atoms traversed ; electrons which derive from the primary β-particle too little energy to enable them to escape from the atom may acquire enough to raise them above the radiation energy level.

We may calculate the number of collisions per cm. in which the transfer of energy from the β-particle to an electron lies between the resonance and ionisation limits, and hence obtain also an estimate of the energy lost in this way per cm. of its path by the β-particle. The calculated energy loss in radiation collisions of this kind amounts, however, to less than 1/10 of the magnitude found above for the energy lost by the β-particle otherwise than in ejecting electrons.

To obtain a sufficient total loss of energy by non-ionising collisions we have to suppose that the β-particle may lose energy in an encounter with an atom even when the encounter is such that the energy lost is a very small fraction of the equivalent of the normal resonance potential.

The conditions along the track of a β-particle, of which the energy is very great compared with resonance or ionising potentials, are very different from those of experiments on ionising potentials, which are made with comparatively slow electrons at low pressures. It is possible that resonance radiations when once excited may be continually overtaking the β-particle and being absorbed and re-emitted along its track. Collisions which would otherwise have been ineffective (unaccompanied by any loss of energy of the β-particle) may possibly be made effective through this absorption of resonance radiation ; at the same time certain collisions which would otherwise have resulted in the production of radiation only, may in the same way become ionising collisions. Again, a portion of the radiation from atoms traversed by the primary β-particle may be absorbed in atoms traversed by the ejected electrons and so assist in producing secondary ionisation.

It may be to such absorption of resonance radiations, already excited by the β-particle in previous encounters, that we have to look for an explanation of (1) the excess of the loss of energy along the path of the β-ray over the sum of the calculated losses due to ejection of electrons and excitement of resonance radiation, (2) the excess of the primary ionisation over that calculated according to Thomson's theory, and (3) discrepancy between the small amount of energy available on that theory from the primary ejected electrons as compared with the number of ions finally produced (10 volts per pair). It is also possible that it may afford an explanation of curvature in β-ray tracks (see Sections 8 and 9).

4. *Ejection of Electrons from the K-Level.*

The number of electrons ejected from the K-level of the nitrogen in 1 cm. of air by a β-particle would according to the Thomson-Bohr theory amount to about 1/120 of those ejected from the outer levels. (It is assumed that the energy of the β-particle is large compared with that required to remove an electron from the K-level.) Thus we should expect rather less than one K-electron to be ejected per cm. of the path of a β-particle of which the range was comparable with 1·5 cms. When, however, the velocity of the β-particle only amounts to a few times that of the K-electrons in the atom (as it does in the last few tenths of a mm. of its range) the chance of ejection of an electron from the K-level is much greater.

There are two ways in which cases of the ejection of an electron from the K-level of an atom might possibly be recognised. The energy of the ejected electron after escaping from the parent atom will be less than if it came from an outer level by the energy difference of these levels; the velocity of the secondary electron as deduced from its range may be expected to be less than that deduced from the deflexion of the primary β-ray. Again the ejection of the K-electron will be followed by the emission of a quantum of K-radiation; this might be absorbed by a neighbouring atom and give rise to a short characteristic β-ray track. Such short β-ray tracks (due to absorption of K-radiations of the gas) are frequently found near the origins of the primary β-rays when these are produced in air by X-rays. They also sometimes occur in the neighbourhood of the ends of β-ray tracks. They are extremely rare near other portions of the tracks. It is possible that such characteristic radiations are much more readily absorbed in the track itself than elsewhere; in the case of such absorption the resulting secondary β-ray would not be immediately distinguishable from one ejected by the direct action of the primary β-ray alone.

5. *Branch Tracks* (Figs. 10, 11, 12, 13).

The chance of occurrence of a branch track exceeding a given length may, on Thomson's theory, be calculated if we know the energy of a β-particle of given range. The energy of a β-particle of 1 mm. range corresponds to about 6,600 volts. (To eject an electron from the K-level of nitrogen or oxygen with velocity sufficient to produce a track of 1 mm. range would require about 400 additional volts.) From Thomson's theory we deduce, that the chance of a branch of longer range than 1 mm. occurring between 1 and 2 cms. from the end of a β-ray track in air at normal pressure is about 1 in 10.

The numbers found by actual counting, while of the right order of magnitude, are somewhat smaller than the theory would predict. In the initial 2 cms. (corresponding to 5 mm. at normal pressure) of 344 tracks in air at a pressure of 19 cms. of mercury there were 12 branches exceeding 4 mms. in length (= 1 mm. at atmospheric pressure); the range of the primary β-rays was between 1 and 2 cms. The number of branches found in this region of the range amounts to 0·07 per cm. of the primary track (at normal pressure) as compared with about 0·10 according to the theory. Again 990 tracks of average range about 1·5 cms. had 65 branches with ranges of more than 1 mm.; the count in this case being made along the whole available length of the primary track. The number of branches per primary track of about 1·5 cm. range is thus about 0·07; according to the theory it should be about twice as great. Many of the tracks were however of less than 1 cm. in range; and, again, of the longer tracks the terminal portion was frequently missing from the photograph; the discrepancy may possibly nearly all be accounted for in this way.

A count was also made of the branches which exceeded 1 mm. in length (= 0·25 mm. in range at normal pressure) in air at a pressure of 1/4 of an atmosphere; the number in the initial 2 cms. of the tracks (= 0·5 cm. at atmospheric pressure) was counted. The average range of the tracks was about 1·5 cm. at normal pressure. In 362 tracks 36 such branches were counted; *i.e.*, a mean of 0·10 branch, exceeding 0·25 mm. in range, per $\frac{1}{2}$ mm. of track of 1·5 cm. range. Substituting for the ranges of the β-particles the equivalent voltages, we may say that the mean number of electrons ejected with energy corresponding to more than 3,300 volts, by a β-particle of energy corresponding to about 25,000 volts, is 0·20 per cm. This is almost identical with the calculated number.

In the great majority of cases of branched tracks the branch is approximately perpendicular to the deviated β-ray track; this is the result to be expected when the encounter is between two equal masses, one of which is initially at rest. The atomic electrons are not at rest, and in addition they may suffer deviations during or after ejection from the atom; so that we should not expect the angle to be exactly 90°. Except however in the case of β-rays of extremely short range the velocity of the electrons within the atom is relatively small.

Branches on the tracks of very fast β-particles from radio-active substances generally make with the deviated β-ray track an angle which is appreciably less than 90°.

There are also other cases in which the angle between the branches differs greatly from 90°. In some cases the explanation may lie in the deviation of the ejected electron by forces within the atom ; but when the primary β-rays are produced by the action of X-rays there is the additional possibility that the ejection of the electron which gives the branch track may also be partly due to the action of X-radiation.

On the assumption that we are dealing with a simple encounter between the β-particle and an electron, we may determine the ratio of the velocity of the deviated β-particle to that initially given to the ejected electron, by measuring the angle through which the β-ray is deflected. We may also get an estimate of the velocity of the β-particle after the encounter, and of the electron after its escape from the atom, by measuring their ranges. It is of interest to see to what extent there is agreement between the values, found by the two methods, for the ratio of the velocity of the β-particle to that of the ejected electron. Even when the plane containing the ray before and after the deviation is nearly perpendicular to the axis of the stereoscopic camera, there is generally an uncertainty of 2° or 3° in the determination of the angle of deviation. This introduces an uncertainty of 10 or 20 per cent. into the determination of the ratio of the velocities by this method. While there may possibly also be error of 10 or 20 per cent. in the measurement of the ranges (on account of the difficulty of measuring along the tracks in three-dimensions) this only corresponds at most to a 5 per cent. error in the measurement of the velocities, if the range is taken as proportional to the fourth-power of the velocity. Measurements were made on 37 branched tracks ; the primary β-rays were due to the action of X-rays on air and had initial velocities less than 10^{10} cm. per second, so that the effective mass did not differ much from that of a slow-moving β-particle. Of these 37 branched tracks 16 showed an agreement between the ratios R_1, R_2, of the velocities obtained by the deviation and range methods respectively, to within 20 per cent. ; the ratios themselves varied between 1 and 3·3. The mean value of R_1/R_2 for these 16 tracks is 1·005 ; so that the two methods give on the whole identical results. As regards the rest of the tracks (except for two in which the ratios of the velocities obtained by the two methods differed by less than 25 per cent.) the differences in the results obtained by the two methods are far outside the range of experimental error.

In a few instances the deflection of the β-ray exceeded the value which would correspond to the range of the branch track. An abnormally large deflection of this kind may be explained as being due to the ejected electron coming from an inner level of the atom and so losing an appreciable part of its energy in escaping; or again as being the result of the β-particle having approached near enough to the nucleus to be deflected by it.

In most of the abnormal cases, however, the deflection of the β-particle is very small in comparison with what might be expected from the range of the branch track. In 17 out of the above 37 tracks the ratio of the velocity of the β-ray to that of the ejected electron, as deduced from the deflection, exceeded twice, in 14 cases three times, in 12 cases six times the ratio as deduced from the ranges. In 10 out of these 12 cases the discrepancy was much greater, the deviation of the β-ray being less than 1/10 of what would correspond to the ratio of the velocities as deduced from the ranges.

An abnormally small deflection accompanying expulsion of a secondary β-particle, like an abnormally large one, may in some cases be due to the deflecting action of the nucleus on the primary β-particle; it is unlikely, however, that nuclear deflection will in more than a few cases happen nearly to neutralise the deflection of the β-particle due to its encounter with an electron.

The expulsion of secondary β-rays of considerable range without corresponding deflection of the primary particle would seem to prove that the energy of the ejected β-particles is not always mainly derived directly from the kinetic energy of the primary β-particle. It is possible that the additional energy of the secondary β-particle, when there is little or no deflection of the primary β-particle, is derived from X-radiation, mainly secondary radiations excited in the air by the primary X-ray beam; radiation of appropriate wave-length may be more easily absorbed in the path of a β-particle than elsewhere.

The branch tracks which are associated with abnormally small deflections of the primary β-ray have in most cases a range of 3 or 4 tenths of a millimetre, corresponding to a velocity of about 4×10^9 cm. per sec. or energy about 4,000 volts. This range is approximately the same as that of the long-range δ-rays produced in air by α-rays. Again, it does not much exceed the calculated range of a β-particle ejected by argon K-radiation (energy = 3,200 volts).

6. *Two Branches from the same Point.*

One or two examples of β-ray tracks with two branches springing from the same point have been found among the photographs. A striking case is that shown in fig. 13 (Plate 22).

The chances against two electrons being independently ejected from molecules so near one another as to be unresolved in the photographs are very great. It is much more likely that the two electrons have been simultaneously ejected from one atom. Such an occurrence is of interest in connection with theories of spectra, both of ordinary light and of X-rays.*

7. *Nuclear Deflections.*

Sudden deviations not associated with branches occur fairly frequently on the β-ray tracks; a deflection of this kind is most naturally regarded as being due to the β-particle passing near the nucleus of an atom. The deviations unlike those due to encounters with electrons (which do not normally exceed 45°) have all values up to 180°. There may or may not be a pair or small group of ions at the bend; it is only rarely that there is a large group or short branch at the bend, due to a close encounter with an electron in the same atom. Examples of nuclear deflections are shown in figs. 10, 16, 17 (Plates 21 and 24).

I have not attempted to make anything approaching a complete statistical study of the nuclear bends; *i.e.*, a determination of the frequency with which any given angle of deviation is exceeded in any given portion of the range of the normal β-particle. This would be a matter for a special research.

It is possible, however, in a stereoscopic picture of β-ray tracks to recognise with some certainty whether a sudden bend exceeds or falls short of 90°. I have made a count of the number of deflections equal to or exceeding 90° in 503 tracks; the observations were confined to the portion of the tracks lying between 5 mm. and 15 mm. from the end of the range measured along the track and reduced to atmospheric pressure. In the 503 tracks there were 44 nuclear deflections of 90° or more in this portion of the range; the limiting ranges, 15 mm. and 5 mm., correspond to energies of approximately 25,000 and 15,000 volts respectively.

Thus in air at atmospheric pressure 8·8 per cent. of the β-particles suffer sudden deflections of at least 90° in the portion of the track lying between 15 mm. and 5 mm. from the end; the energy of the β-particle falls from about 25,000 to about 15,000 volts in this section of the path.

* S. Rosseland, *loc. cit.*

According to Rutherford's theory* of nuclear deflections, the fraction of the whole number of β-particles which suffers deflections exceeding 90° in a distance dx is $\mathrm{K}dx$, where

$$\mathrm{K} = \pi\mathrm{N}\left(\frac{\mathrm{E}e}{2\mathrm{T}}\right)^2$$

and N is the number of atoms per c.c., E, e the charges of the nucleus and β-particle respectively, and T the kinetic energy of the β-particle. The variation of voltage V along the path of the β-particle is given approximately by $\mathrm{V}^2 = 21000^2\, x$, where x is measured along the track from the end of the range; so that

$$\mathrm{T}^2 = \left(\frac{\mathrm{V}e}{300}\right)^2 = \frac{e^2}{300^2}\times 21000^2 x = 4{\cdot}9\times 10^3 e^2 x.$$

Thus the fraction of the β-particles which suffers a deflection exceeding 90° between 15 and 5 mm. from the end of the range is

$$\mathrm{F} = \int \mathrm{K}\, dx = \pi\mathrm{N}\,\frac{\mathrm{E}^2 e^2}{4}\int\frac{1}{\mathrm{T}^2}\, dx$$

$$= \frac{\pi\mathrm{N}\mathrm{E}^2}{4\times 4{\cdot}9\times 10^3}\int_{0\cdot 5}^{1\cdot 5}\frac{1}{x}\, dx$$

$$= \frac{\pi\mathrm{N}\mathrm{E}^2}{19{\cdot}6\times 10^3}\log 3.$$

Now F was found from the above observations to be $8{\cdot}8\times 10^{-2}$; N, the number of atoms in air at atmospheric pressure and 15° C., is $5{\cdot}5\times 10^{19}$; we may use the data to deduce E, the nuclear charge

$$\mathrm{E}^2 = \frac{8{\cdot}8\times 10^{-2}\times 19{\cdot}6\times 10^3}{\pi\times 5{\cdot}5\times 10^{19}\times 1{\cdot}1}$$

$$\mathrm{E} = 3{\cdot}1\times 10^{-9}\ \text{e.s.u.} = 6{\cdot}5e.$$

This is very near the theoretical nuclear charge, $7e$, of the nitrogen atom.

8. *Curvature of β-ray Tracks.*

Every case of ejection of an electron by a β-particle involves a change of momentum of the β-particle, mainly in a direction perpendicular to its path and in general therefore a deviation of the primary ray. The deviation is generally easily measurable when the secondary β-particle acquires sufficient energy to enable it to produce a visible branch track. In the great majority of cases, however, the secondary electron only acquires a small fraction of

* 'Phil. Mag.,' vol. 21, p. 668 (1911).

the energy of the primary β-particle, and the individual deviations of the β-ray are small.

To do no more than just eject an electron from an atom, energy corresponding to the ionising potential (of the order of 10 volts) must be supplied. If this has come from a β-particle of range 1·5 cm. (energy about 25,000 volts) the deflection of the β-particle, given approximately by the ratio of the velocities corresponding to the above voltages, will be about 1°. This is the smallest deviation to be expected, according to the simple theory for any case of ejection of an electron by a β-particle having the above energy, and of such ejections there are nearly 100 per cm.

In addition to this large number of small deviations due to ionising encounters with the electrons of the atom, a quite comparable number of deflections of similar amount is to be expected from nuclear collisions.

That a number of successive small deviations should sometimes happen to be all in the same direction, and give to a β-ray track the appearance of possessing a continuous curvature over a short distance, is perhaps not surprising. But the curvature sometimes continues over such remarkably long distances that it is difficult to believe that it is accidental. It is quite possible to get instrumental distortion of tracks, due to air motion and other disturbing influences, but I believe that such distortion is absent in the photographs now published. The occurrence of perfectly straight tracks—of α-rays or fast β-rays—in the pictures, close to curved β-ray tracks (fig. 1), and of β-ray tracks in which the earlier portion is straight and curvature only appears in the latter part of the track (fig. 10), is sufficient evidence that the curvature belongs to the original path of the β-ray.

A thorough statistical study of the curved tracks has not been attempted. The observations which have been made indicate that curvature is not an essential property of the β-ray track, which gradually becomes more and more evident as the end of the path is approached ; but rather that in certain cases, as a result of some particular kind of encounter having occurred, succeeding encounters are affected by a "bias" which favours deflection in one direction. When the curvature appears, its magnitude corresponds to an average deviation in the favoured direction of from 1° to 3° for each ionising collision ; *i.e.*, it is of the order of magnitude to be expected if the bias were sufficient to make nearly all the ionising collisions result in deviations towards one side of the path, the magnitude of the deviation due to an ionising collision remaining unaltered. Both Shimizu and Compton* have called

* A. H. Compton, 'Phil. Mag.,' vol. 41, p. 279 (1921).

attention to the curvature of the tracks in some of my earlier photographs, and both drew the conclusion that, to explain the curvature, the β-particle must itself be capable of acquiring a bias by being set in rotation. There is, however, another alternative which appears to me to be a more probable one.

Many of the atoms which the β-ray has traversed have been put in a condition to emit radiation; these radiations may be continually overtaking the β-particle and affecting the nature of its succeeding encounters with electrons of other atoms, these encounters at the same time determining the absorption of the radiation. The bias causing the curvature may thus not lie in the β-particle, but in the field of radiation in which it is moving.

9. *Effects of Secondary Radiations Overtaking the β-Particle.*

Let us suppose that Thomson's equation is used to calculate the number of occasions on which the energy transferred from the β-particle to an electron exceeds any given value. In all cases in which the calculated energy transferred falls short of that necessary to bring the electron from the orbit in which it is situated to the next stationary orbit which it can occupy, there is no transfer of energy. The deviation of the β-particle due to an encounter of a given degree of closeness with an electron will depend on whether or not this transference takes place; we may describe a collision as effective in the first case and ineffective in the second.

Any influence which converts an ineffective into an effective collision will produce a definite effect on the resulting deviation of the β-particle. In an ineffective collision we might picture the absence of any transfer of energy as being due either to the force between the β-particles and electron being zero instead of having the calculated value, or, more naturally, to the force causing no displacement of the electron relatively to the nucleus; in the latter case the force is in effect exerted by the β-particle on the relatively very large mass of the nucleus or of the atom as a whole. An ineffective collision would on the first view cause no deviation of the β-particle, on the second view twice as large a deviation as an effective collision; thus the difference in the deviations due to an effective and an ineffective collision of a given degree of closeness is the same on either view, but the sign of the difference is opposite.

Any agency which converted what would otherwise have been ineffective collisions into effective ones, only when these collisions were such as to cause deviation of the β-particle in one direction but not in the opposite, would give a bias or curvature to the path of the β-particle. Radiation from an atom which has already been traversed by the β-particle may be such an agency.

We may perhaps illustrate the essential features of the matter by considering a model of the atom in which the electrons are supposed to be initially at rest, each at its normal energy level. A β-particle may make a large number of ineffective collisions, but before it has travelled more than a small fraction of a millimetre it is likely to pass sufficiently near to an electron to displace it to the resonance energy level, or to a higher, let us say, the nth level. Let us suppose that the displaced electron immediately falls back to its normal level and that the energy radiated is all absorbed by an electron with which the β-particle is now making what would otherwise have been an ineffective collision; a collision, for example, which would not have given to the electron energy sufficient to bring it from the normal level to the resonance level, but which would have been able to bring it from the nth to the $(n+1)$th level. The original displacement of the first electron by the encounter will be perpendicular to the path of the β-particle; let it be in the y direction. The displacement of the second electron due to the falling in of the first will tend to be in the direction y. It is only when the collision tends to displace the second electron in the y direction, as distinct from the $-y$ direction, that the radiation will tend to convert an ineffective into an effective collision.

The second electron may at once in turn fall back, with emission of radiation, which again overtakes the β-particle and affects the nature of a subsequent collision. We may thus picture the radiation as being handed on from atom to atom along the path of the β-particle, and converting collisions, which would otherwise have been ineffective, into effective collisions, in such a way as to give a bias to the β-ray. Eventually the radiation would take part in the ejection of an electron and so cease to be handed on along the path of the β-particle.

It is possible that not only resonance radiation but characteristic X-radiations may be transmitted along the path of the β-particle in the above manner. We might explain in this way some of the results of Section 5, *e.g.*, the occurrence of branch tracks with abnormally small deviation of the β-ray. Quite an appreciable proportion of the β-particles ejected by the primary X-rays are likely to originate in argon atoms; the argon K-radiation thus excited may possibly be transmitted from one argon atom to another along the path of the β-particle until it is finally absorbed with ejection of an electron from some other atom through which the β-particle passes. The branch tracks accompanied by abnormally small deviations of the β-particle were, as pointed out in Section 5, mainly of ranges only slightly exceeding that corresponding to argon K-radiation.

10. *Some Less Frequent Occurrences.*

An isolated sphere track sometimes occurs in the immediate neighbourhood of the end of a β-ray. These sphere tracks are in all probability due to characteristic radiations from an atom, from the K-level of which the primary β-ray has ejected an electron. The chance of such ejection is particularly great near the end of the range of the primary β-particle, when its energy does not greatly exceed that required to eject a K-electron; and again there is the possibility, suggested in Section 9, that the K-radiation may have originally been excited further back in the path of the β-particle, and been handed on from atom to atom till it escapes at the end.

When a β-ray ends in or near the path of the primary beam of X-rays, the occurrence of an associated short-range track within the primary beam is apparently a much more frequent phenomenon (fig. 16); a long track may also sometimes have its origin in a similar position, *i.e.*, within the primary X-ray beam and close to the end of another track. These effects are in accordance with the results of Part I, Section 8; the secondary β-ray is apparently due to a combined action of primary and secondary X-rays.

The almost complete absence of isolated sphere tracks or scattered ions in the spaces between the long β-ray tracks, outside the primary X-ray beam, is very striking. Collisions resulting in the ejection of K-electrons cannot be very rare along the paths of the β-particles (Section 4); it is possible that the resulting K-radiation, as suggested in Section 4, is generally absorbed by an atom lying in the track of the primary β-ray. A few cases of sphere or other tracks have, however, been observed to originate outside the track of a primary β-particle, but very near a sudden bend in its path.

There is one very remarkable case of this kind in which a secondary β-ray track of considerable range (about 8 mm.) starts close to a sudden bend, of nearly 90°, in the track of a primary β-ray. The expansion during the series of experiments to which this belongs was completed during the passage of the X-ray discharge (Part I, Section 9). The diffuse character of the primary β-ray track, and the sharpness of that of the secondary ray, show that there was a considerable interval—of the order of 1/1000 of a second—between the ejection of the primary and secondary β-particles.

A few cases have been encountered in which the track of a β-particle is "broken," in the sense that it appears to come to a sudden end, to continue its course again with diminished velocity (as shown by the increased ionising effect) along a laterally displaced nearly parallel line ; the direction of motion may or may not be reversed (figs. 14 and 15). The appearance of these broken tracks suggests the production of a polarised X-radiation by sudden stopping of a β-ray (as a result of a nuclear collision), and the absorption of this radiation with ejection of an electron in a direction nearly parallel to the path of the primary β-particle.

A remarkable event is shown in fig. 17, where two long-range β-particles, which undoubtedly form a pair (Part I, Section 8), have been emitted upwards and downwards respectively from atoms exposed to a narrow beam of X-rays. The lower β-particle has suffered a nuclear collision, with complete reversal of its direction, and has approached very closely to the track of the other particle ; the two tracks have the appearance of being twisted around one another, as if one particle were in effect attracted by the other or by its tracks. This remarkable occurrence may be a mere accident ; it is however not inconceivable that secondary radiations from atoms traversed by one β-particle may so influence the nature of the encounters made by a second β-particle, which passes almost simultaneously in the immediate neighbourhood, as to cause an apparent attraction between the particles.

Summary of Results.

The tracks of fast β-particles are very nearly straight over distances of several cms. In the last few cms. of the range the deviations are large and are of three kinds : (*a*) sudden deviations often through large angles up to 180°, the result of a close approach to the nucleus of an atom ; (*b*) sudden deviations ranging up to 45°, due to a close approach to an electron which is in consequence ejected to form a branch track, generally approximately at right angles to the deflected primary track ; (*c*) gradual deviations due to an accumulation of deviations of *a* or *b* type, individually too small to be detected.

The range of the β-ray as measured along the track is approximately proportional to the square of the kinetic energy, or to the 4th power of the velocity (Whiddington's law), for ranges from about 0·1 cm. to 1·5 cms. ; the range is 1 cm. when the kinetic energy of the particle is the equivalent of about 21,000 volts.

The primary ionisation (*i.e.*, number of atoms from which electrons are ejected by the direct action of primary β-ray) is about 90 per cm. for a velocity of 10^{10} cm. per sec. and is approximately inversely as the square of the velocity.

The total ionisation per cm., including that due to secondary β-particles of range too short to form visible branch tracks, is about 3 or 4 times as large as the primary. The primary ionisation is in agreement with Thomson's theory, if the minimum energy which the β-particle has to give to the electron to eject it is about 7 volts—approximately the resonance potential (not the ionisation potential) of nitrogen.

In portions of some of the tracks not only is the primary ionisation (number of atoms from which the β-particle has ejected an electron) recorded, but the ions which each of these electrons has itself produced are made visible and may be counted.

The number of tracks which have branches exceeding a given range, *i.e.*, which eject electrons with kinetic energy exceeding a given value, is in general agreement with Thomson's theory.

The number of tracks with nuclear deflections exceeding 1 right angle is in good agreement with Rutherford's theory and gives for the charge of the deflecting nucleus the value $6 \cdot 5\ e$, almost identical with the theoretical $7e$ of nitrogen.

In many cases of branching the ratio of the velocities as given by the ranges of the two branches is in agreement with the ratio obtained from the angles; but there are other cases in which a branch track of considerable range occurs accompanied by only a very small deviation of the primary ray.

It is suggested that many features of the β-ray tracks, including the curvature which sometimes appears, may be due to radiations which are excited in atoms by the passage of the β-particle; the radiations continually overtaking the β-particle and affecting the nature of its collisions with electrons in atoms subsequently traversed.

The work of which an account is given in this and the previous paper was carried out at the Solar Physics Observatory. I have to thank the Director, Prof. Newall, for providing me with all facilities for carrying on the work. I owe much to discussions I have had with him and with Mr. Milne. I am indebted to Mr. Stanley for the help he has given in the design of apparatus, and for constructing it in the Observatory workshop, and to Mr. Manning for making enlargements of many hundred stereoscopic pictures, a few of which are reproduced.

Fig. 1 (X 4).

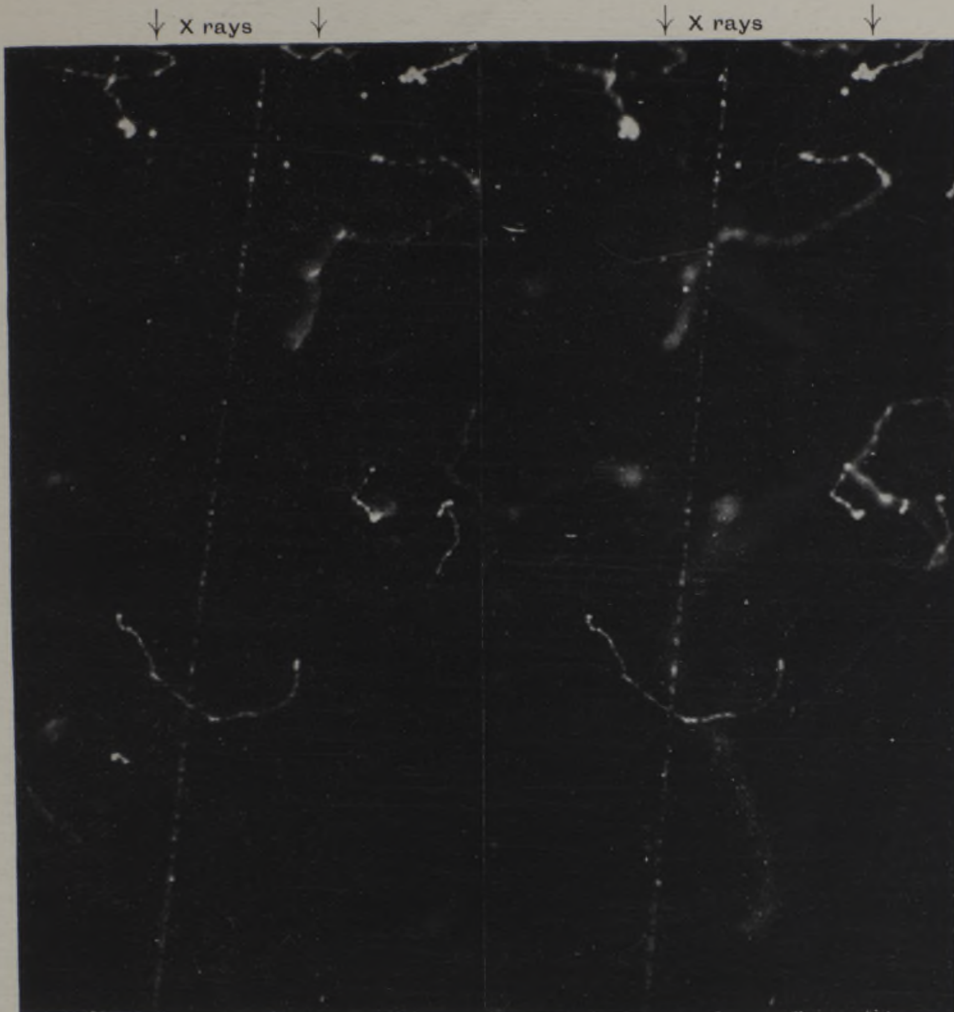
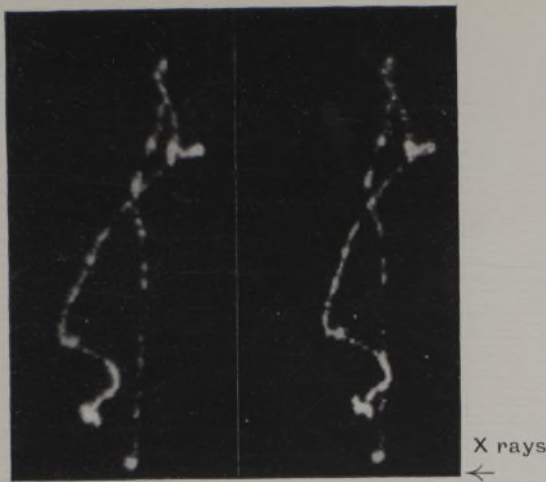


Fig. 2 (X 4).

Fig. 1. Fast and slow β ray tracks. Final pressure 55 cms.
,, 2. Final air pressure 20 cms.

Fig. 3 (X 8).



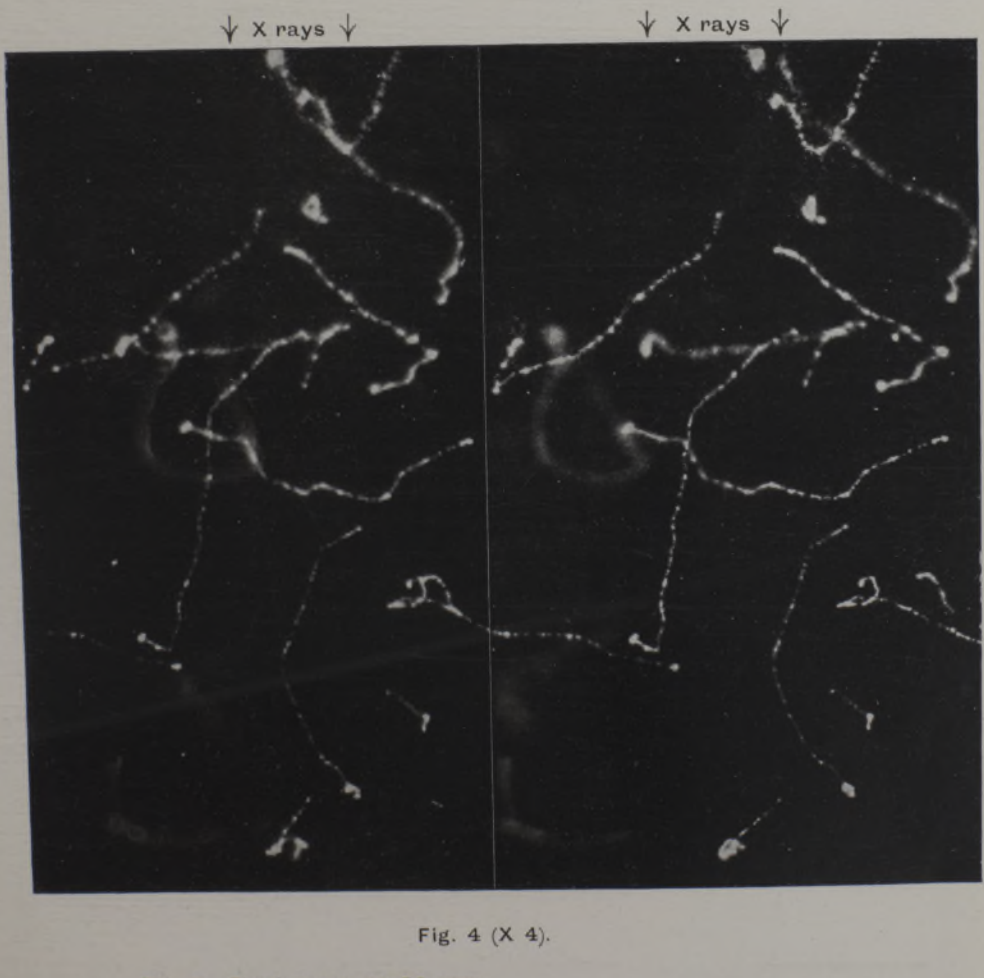
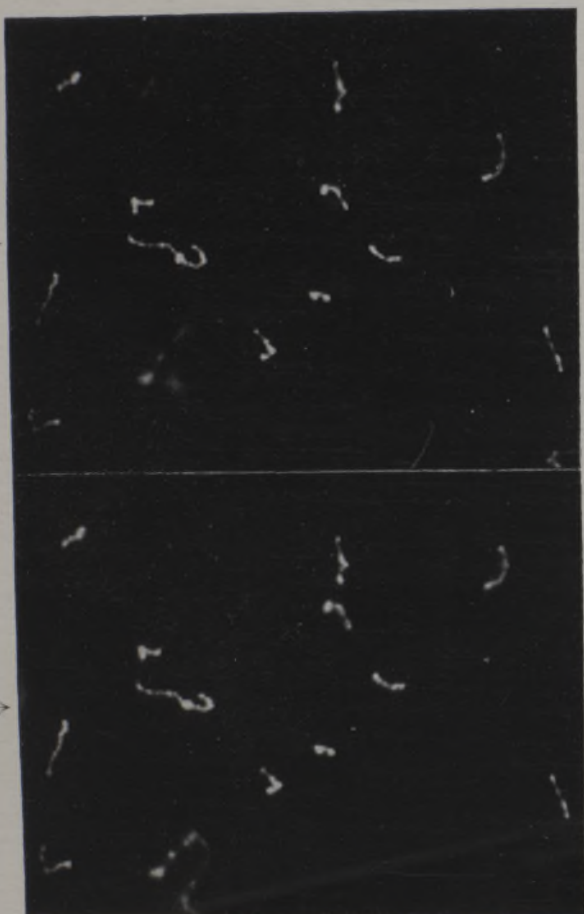


Fig. 4 (X 4).

Fig. 3. Final pressure 50 cms.
Fig. 4. β rays due to Silver K radiations. Final pressure 53 cms.

Fig. 5 (X 4).



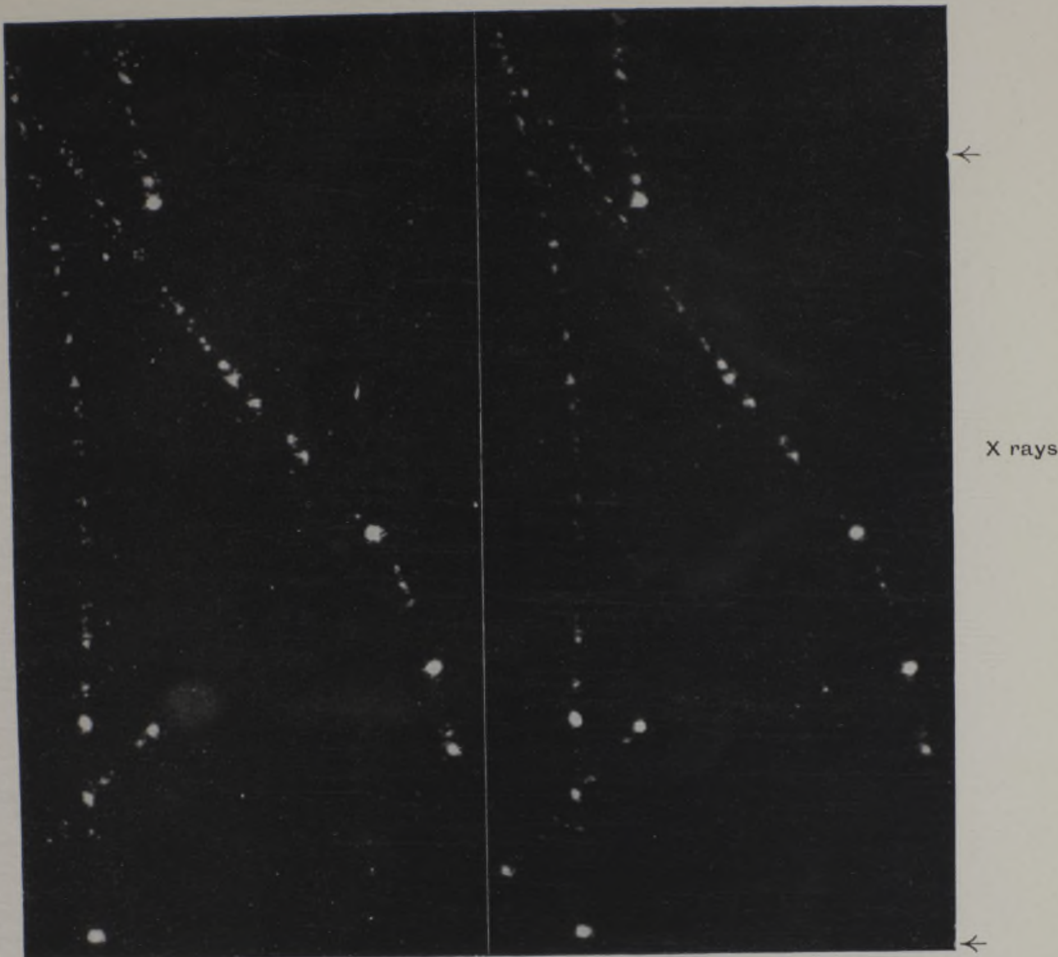
β rays due to copper K radiations.

Final pressure 53 cms.

Fig. 6 (X 8).

Track of fast β ray showing groups resolved. Final pressure 20 cms.

Fig. 7 (X 8).



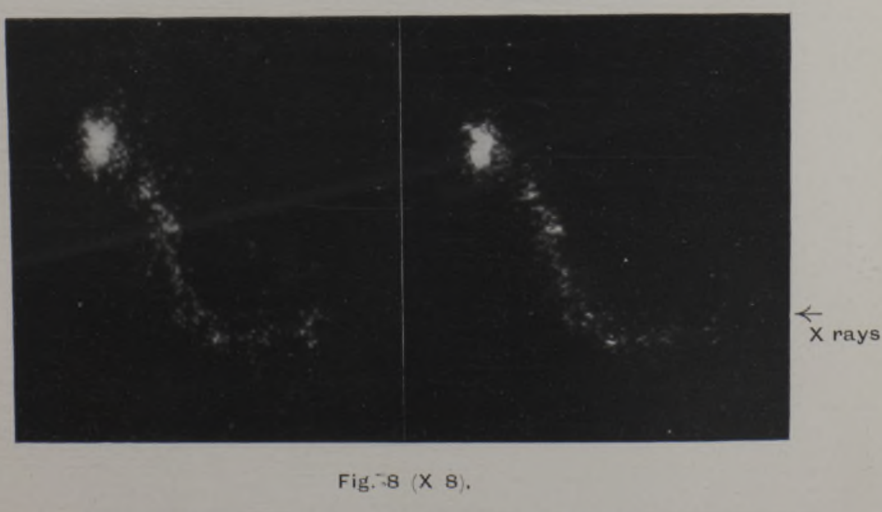


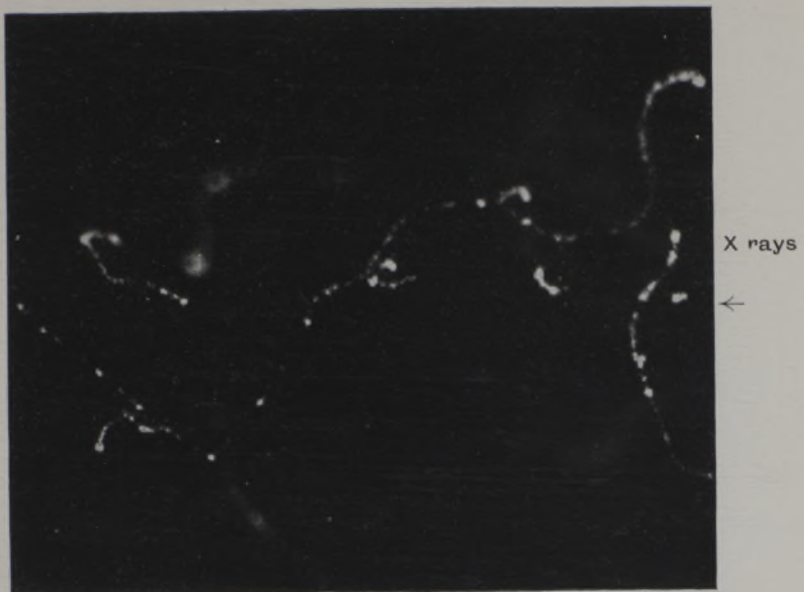
Fig. 8 (X 8).

Resolved tracks (Section 3). Fig. 7. Final pressure 18 mm.
Fig. 8. Final pressure 11 cms. "Fish track" (Part 1, Section 7).

Fig. 9 (X $2\frac{1}{4}$).

Tracks divided into positive (upper) and negative (lower) components. The X rays passed before the expansion and the positive and negative ions travelled upwards and downwards respectively under the action of the vertical electric field before being fixed by condensation of water. Final pressure 50 cms.

Fig. 10 (X 4).



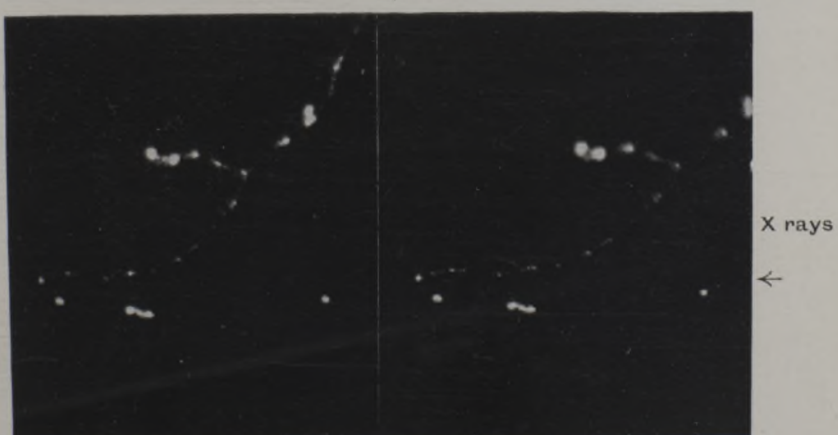
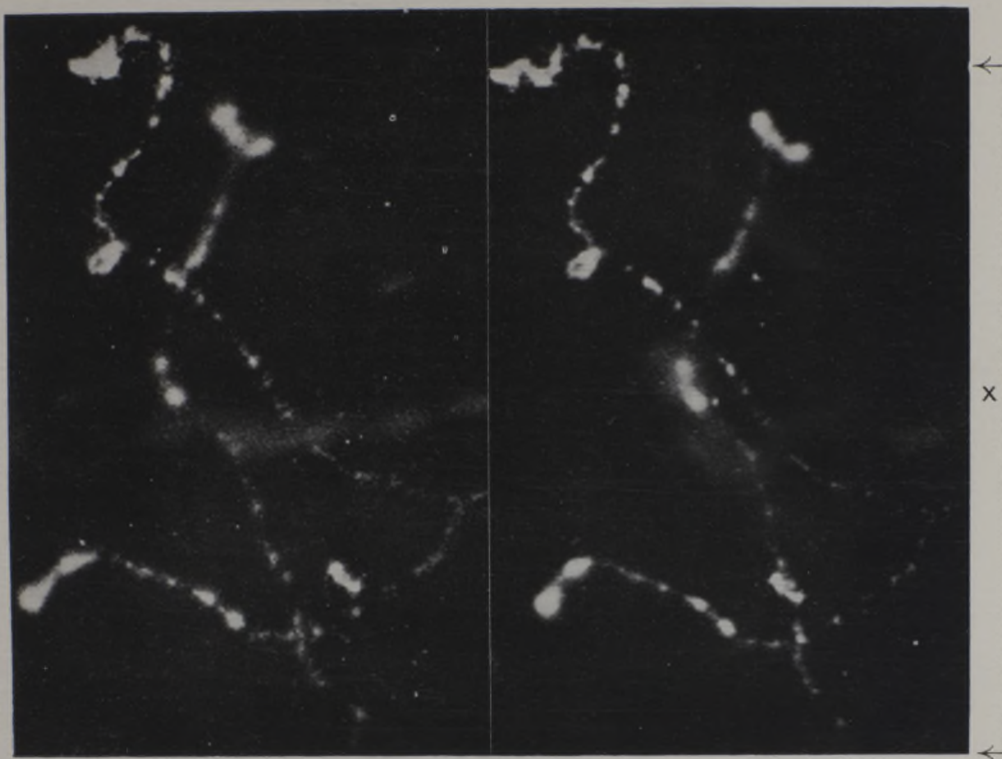


Fig. 11 (X 4).

Fig. 10. Track starts with large backward component (Part I, Section 6). Initial straight portion, nuclear bend, branches; curvature in later portion of track. Final pressure 20 cms.

Fig. 11. Branched track. Final pressure 20 cms. Near origin of main track is associated "sphere" track (Part I, Section 8).

Fig. 12 (X 8).



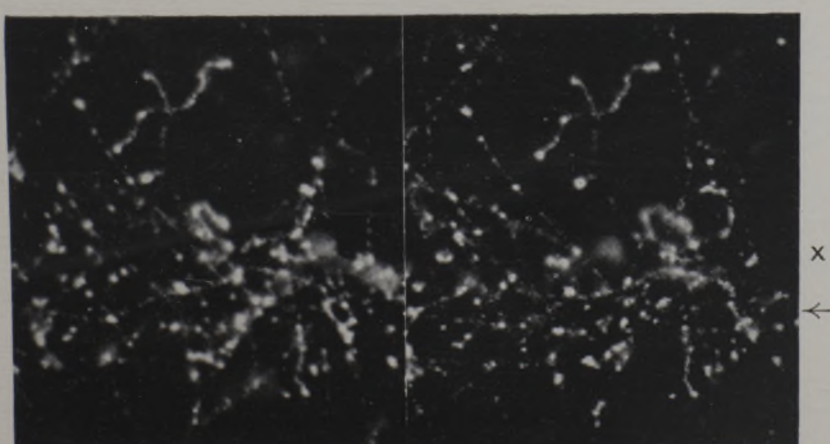
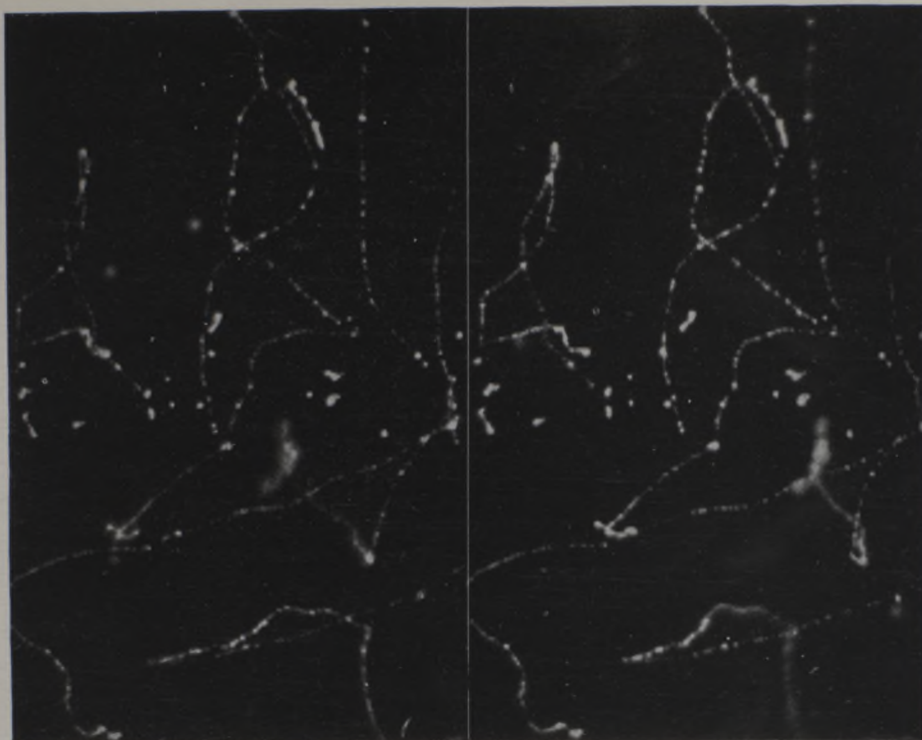


Fig. 13 (X 4).

Fig. 12. Branched track. Final pressure 18 cms.

„ 13. Two simultaneous branches (Section 6). Final pressure 18 cms.

Fig. 14 (X 4).



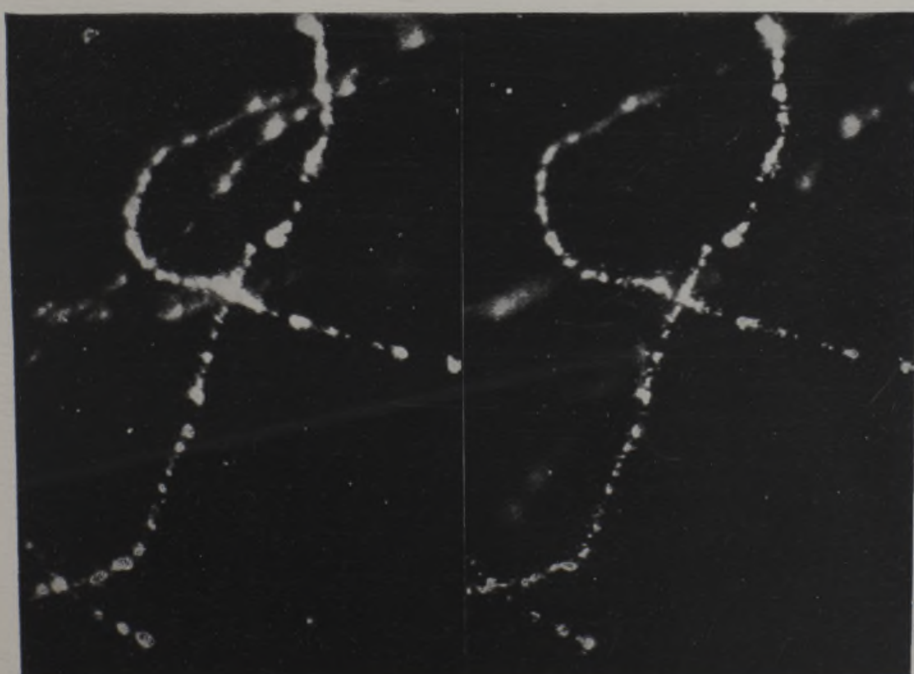
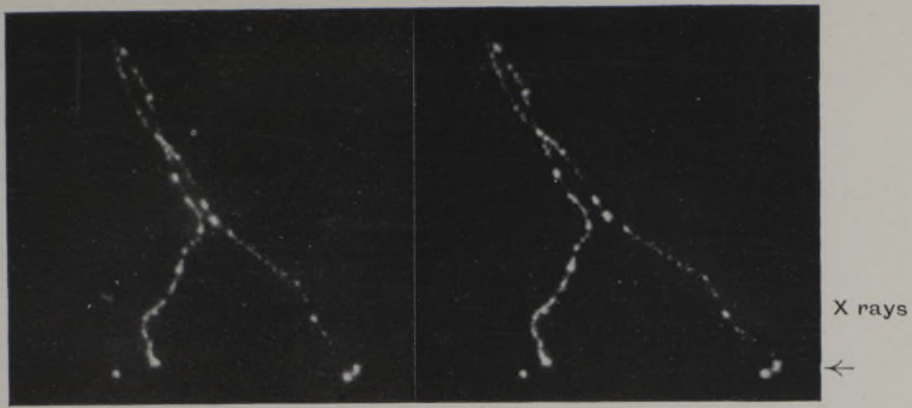


Fig. 15 (X 8).

Broken tracks. (Section 10.) Fig. 14. Final pressure 50 cms.
Fig. 15. Final pressure 19 cms.

Fig. 16 (X 8).



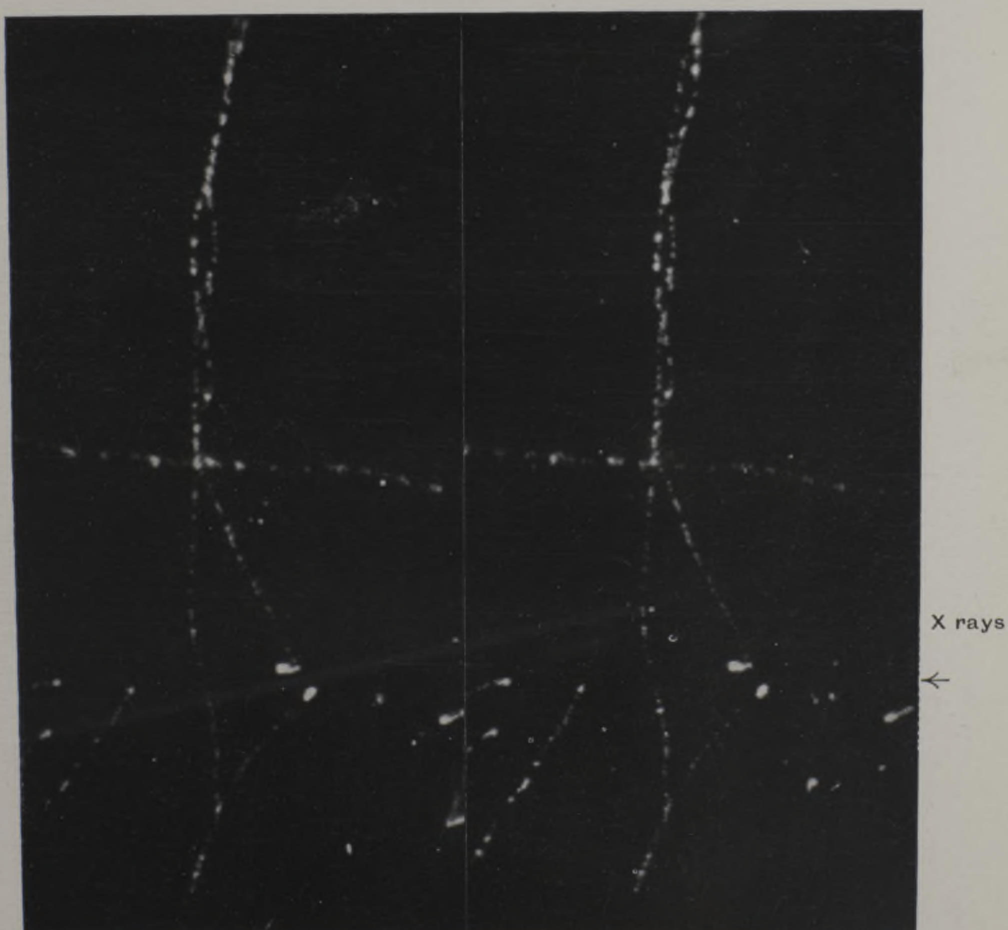


Fig. 17 (X 8).

(Section 10.) Fig. 16. Final Pressure 19 cms.
„ 17. Final pressure 55 cms.