# Investigations on $X$ Rays and $\beta$ Rays by the Cloud Method. Part 1. – $X$ Rays.

C.T.R. Wilson
Cambridge
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## *1. Introduction.*

The method used in these investigations is that which was described in papers communicated to the Royal Society in 1911 and 1912.[1] 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 –$\alpha$ – or $\beta$–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 $\beta$–particle, when it occurs among a crowd of tracks of slower

[1] Roy.Soc.Proc., A, vol. 85, p. 285, and v. 87, p. 277.

$\beta$–particles, gives very convincing evidence that the complicated forms of the latter are not due to instrumental distortion.

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 $\alpha$–ray tracks, the arrangement used by Shimizu[2] 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 $\beta$–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 $\beta$–particles ejected from atoms by the $X$–rays, and not merely the total ionisation; if each $\beta$–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 $\beta$–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 $\beta$–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 $\alpha$— and $\beta$—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.

[2] 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 tabes 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 by $X$–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 trades should be momentarily illuminated after a very short interval. As in the early experiments, the momentary flash of $X$–radiation which acts 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 awing, 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 $X$–raya. No attempt has been made to confine the exposure of the cloud–chamber to these rays to the period between the production of the supersaturated condition and the passage of the illuminating spark. Such photographs, therefore, show not only the sharply defined tracks of $\alpha$– or $\beta$–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 insetted 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 ($\beta$–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 $\beta$–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 he expected from the absorption of X–rays in air*

According to the quantum theory, when $X$–radiation of definite frequency $v$ 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 $hv$. Each quantum absorbed by the air causes the ejection of an electron and is thus represented by a $\beta$–ray track in the cloud picture. Of the quantum of energy $hv$ 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 electron from the atom, the rest is represented by the kinetic energy of the emergent $\beta$–particle, The velocities and therefore the ranges of the $\beta$–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 $\beta$–particles ejected by $X$–radiation of wave length $\lambda$ from the $K$–levels of atoms of each of the different constituent elements of the air is approximately proportional to $Z^4\lambda^3N$, where $Z$ is the atomic number and $N$ is the number of is approximately q proportional to $Z^4\lambda^3N$, 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 $\beta$–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 $\beta$–particles to be ejected from the outer levels of atoms of these various elements.

The $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–ray tracks corresponding to the various lines in the magnetic spectrum in experiments such as those of de Broglie.[3]

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 $\beta$–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 $\beta$–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 $\beta$–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 $8 \times 10^{-3}$ 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 $\beta$–rays radiate from the target;

[3] Journal de Physique, vol. 2, p. 265 (1921).

the absence 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 $\beta$–ray tracks, due to elections 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 2/3 of atmospheric pressure, are due to the ejection, by the characteristic $K_\alpha$ and $K_\beta$–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 $\beta$–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 $\beta$–rays have been produced by the direct action of the primary $X$–rays on the air. One $\beta$–particle has been ejected from the copper plate, and one $\beta$–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 $\beta$–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 $\beta$–ray ejected by the secondary radiation indicates that it is due to an $L$–radiation from the atom of platinum from which the primary $\beta$–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$K$-radiations from these metals.

The ranges of the $\beta$–rays produced in air by the $K$–radiationa 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 $\beta$–ray spectrum. The range which recurred with maximum frequency is (in accordance with tile greater intensity of the $K$ 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 $K_\alpha$–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 $K_\beta$–radiation. The $\beta$–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 $\beta$-rays ejected from oxygen or nitrogen by the $K_\alpha$– and $K_\beta$–rays from copper are about 1.3 mm. and 1.7 mm. respectively; those ejected by the $K_\alpha$– and $K_\beta$–radiations of silver have ranges of about 11 mm. and 15 mm.

Putting the kinetic energy of the ejected $\beta$–particle equal to the difference between the energy ($hv$) 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 $\beta$–particles ejected the silver $K$ and $K_\beta$–radiations are 21.700 and 24.600 volts approximately.

The results of these measurements of the mean ranges of $\beta$–particles of different kinetic energies are represented approximately by the formula $V = 21.000R^{1/2}$, where $V$ is the kinetic energy of the particle expressed in volts and B 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[4] connecting the range and velocity of a $\beta$–particle. The velocity of a $\beta$–particle of range 1.5 cm. is nearly 1/3of 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 $1/2m_0v^2$ by nearly 10 per cent.; for higher velocities the relation between range and kinetic energy is likely to be less simple.

The tracks of $\beta$–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.

[4] Roy.Soc.Proc., A, vol. 86, p. 360 (1912).

## *5. Different classes of $\beta$-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 $0.4A^\circ$ – three classes of $\beta$–ray tracks 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 3 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 this 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 elections 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 $0.5A^\circ$. 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 $\beta$–particles. . - “Sphere” tracks are probably in all cases merely the tracks of very short range $\beta$–rays; any $\beta$–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 $\beta$–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 $\beta$–particle which produced the long track. There are, however, other cases of association of $\beta$–rays in pairs which cannot be explained so simply. (See section 8.)

## *Direction of ejection of the $\beta$–particles*

(a) *Polarisation.* – In almost every stereoscopic picture of the tracks of $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–particle does not depend simply upon its velocity of ejection, i.e., upon the wave–length of the radiation absorbed. The $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–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, mach 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.[5] 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.

[5]Richardson, "Electron Theory of Matter."

Tracks with a very large forward inclination are, however, mainly of long 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 $\beta$–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 $\beta$–particles of all ranges with a fairly accurate measurement of the angles is likely to lead to interesting results.

## *7. Short–range $\beta$-rays: "sphere,' "comma" and "fish" tracks*

The intensity of the ionisation in the final tenth of a millimetre of the range of an ordinary $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–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 $A^\circ$.

It is just to this region of the spectrum that Barkla[6] and Crowther[7] have assigned the wave–length of the $\beta$–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 $\beta$–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 $\beta$–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

[6] Barkla, Phil.Trans., A, vol. 217, p. 315; Phil.Mag., vol. 34, p. 270 (1917).
[7] Crowther, Phil.Mag., vol. 42, p. 719 (1921).

radiation. Again the nature and relative number of the short tracks was not found to depend on the material of the screen.

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[8] 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

[8] "Secondary Radiations produced by $X$–rays," Bull. Nat. Research Council, Washington (1922).

direction and a kinetic energy ${}^1/_2mu^2 =^1 /_2h\nu u/c$.

Let us suppose that it is only the $K$–electrons which are effective in this 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 ${}^1/_2mu^2$ 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 ${}^1/_2mu^2$ 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 $\beta$–ray tracks considered in the nest section.

## *8. Association of $\beta$–ray tracks in pairs or groups*

The $\beta$–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 $\beta$–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" $\beta$–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 $\beta$–ray starts from the same origin. In some cases there is merely an enlarged head to the long $\beta$–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 $\beta$–ray. The effect of very short–range $\beta$–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 $\beta$–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 $\beta$–ray tracks may be essentially the same as that of the other types (classes 2, 3 and 4) in which the two $\beta$–partides 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 $\beta$–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 $\beta$-particle, ejected from a second atom by the action of the $K$–radiation of the atom from which the faster $\beta$–particle was ejected. The $K$–radiations from oxygen or nitrogen would give rise to $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–ray tracks are accompanied by sphere tracks (other than those which appear as beads on the $\beta$–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 $\beta$–ray tracks themselves.

With $X$–radiation of frequency sufficient to produce $\beta$– 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 $\beta$–ray is thus shown to be much more likely to eject a $\beta$–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 die 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.

## *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 $\beta$–rays is to be regarded as primary the other as due to radiation from the atom from which the primary $\beta$–particle has been ejected;then to explain the experimental results we must conclude that this secondary radiation is much more likely to eject a $\beta$-particle from an atom exposed to the primary radiation than from one lying outside the primary beam.

When the primary beam was about 0.5 mm. in air at 50 cm. pressure. In a wide beam distance up to 5 or 6 m. 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 nun. 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 $\beta$-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 $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–ray tracks of a pair to be similar might be interpreted as meaning that the $\beta$–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 $\beta$–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 abort wave–length in traversing air cause the ejection of two classes of $\beta$–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 remaning 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 $\beta$–particle or of that which gives the short–range forward–directed $\beta$–particle. Then all the various types of pairs–all possible combinations of long and short $\beta$–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 $\beta$–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 $\beta$–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 $\beta$–ray tracks are produced in air by the primary action of $X$–radiation of wave–length. less than about $0.5A^\circ$ – (a) those of ejected electrons with initial kinetic energy comparable to a quantum of the incident radiation, and (6) 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 $\beta$–particles being in one plane–that containing the direction of the cathode rays in the $X$–ray tube.

(5) $\beta$–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.