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Proc. R. Soc. Lond. A 1906 **77**, 247-255
doi: 10.1098/rspa.1906.0021

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In conclusion, I have to thank Professor Schuster for lending me the radium used in these experiments. To Dr. Hutton I am indebted for the kind way in which he placed his electric furnaces at my disposal, and for his advice as to the best methods of obtaining the temperatures required.

Polarisation in Secondary Röntgen Radiation.

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(Communicated by Professor J. J. Thomson, F.R.S. Received January 17,—Read February 8, 1906.)

In a paper on "Polarised Röntgen Radiation,"[*] the writer gave an account of experiments which demonstrated the partial polarisation of a beam of X-rays proceeding from the antikathode of an X-ray focus-tube, and verified the theory previously given[†] of the production of secondary X-rays in light substances.[‡]

In that paper it was shown that the secondary radiation proceeding in a direction perpendicular to that of propagation of the primary radiation from certain substances placed in that primary beam should, according to the theory put forward, be plane polarised. From gases, however, the secondary radiation was not sufficiently intense to produce a tertiary of measurable intensity, and thus the polarisation of the secondary from them was not verifiable. On the other hand, though heavy metals were found to emit secondary radiation of sufficient intensity and ionising power to produce appreciable tertiary effects, in these metals the production of secondary radiation is a more complex phenomenon, and evidence of polarisation of the secondary beam is not to be expected from experiments upon them.

For the secondary radiator a substance had to be chosen which emitted a radiation of considerable intensity, yet differing very little in character from the primary. It had been shown that from such substances the intensity of radiation is proportional merely to the quantity of matter passed through by the primary of given intensity. A substance permitting the passage of the

[*] 'Phil. Trans.,' A, vol. 204, 1905, pp. 467—479.

[†] J. J. Thomson, 'Conduction of Electricity through Gases,' p. 268; C. G. Barkla, 'Phil. Mag.,' June, 1903, and May, 1904.

[‡] More precisely, substances of low atomic weight.

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primary beam through the greatest mass was therefore the most suitable for the experiment, that is a substance absorbing the radiation as little as possible. As the absorption per unit mass diminishes with the atomic weight,* the less the atomic weight of the substance the greater is the energy of the primary beam transformed into energy of secondary radiation. Preliminary experiments showed that it was possible, by using carbon as the radiator, to produce a secondary beam of X-rays of great intensity and capable of setting up a tertiary giving quite an appreciable ionisation in air.

The following experiments were then undertaken in order if possible to produce and give proof of an almost complete polarisation in a beam of Röntgen rays, and thus to further verify the theory of the production of secondary X-rays in substance of low atomic weight:—

A mass of carbon was placed near an excited X-ray tube so as to be subject to a primary beam of considerable intensity. It was then the source of a secondary radiation, the total energy of which was quite a large fraction of the energy incident upon it. A beam of this secondary radiation proceeding in a direction perpendicular to that of propagation of the primary falling on the carbon was studied.

In this secondary beam was placed a second mass of carbon, and the intensities of tertiary radiation proceeding in two directions at right angles and perpendicular to the direction of propagation of the secondary beam were observed by means of electroscopes placed in its path. The X-ray tube was turned round the axis of the secondary beam, while everything else was fixed, and the relative intensities of the tertiary radiations observed for different positions of the tube.

It was found that the intensity of tertiary radiation reached a maximum when the directions of propagation of the primary and tertiary were parallel, and a minimum when they were at right angles, showing the secondary radiation proceeding from carbon in a direction perpendicular to that of propagation of the incident primary to be polarised. As shown below, the amount of polarisation was enormous in comparison with what had been found in the primary beam proceeding direct from an X-ray tube, and indicated almost complete polarisation of the secondary beam.

The details of the experiments are given below.

A thick square plate of carbon (8 × 8 × 1·2 cm.) and an X-ray tube were place inside a large lead-covered box in positions shown in the figure. The faces of the plate (which was near a rectangular aperture C_1 in the side of the box) were equally inclined to vertical and horizontal lines parallel to the sides of the box, and the face near the aperture was exposed to radiation

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* Benoist, 'Journal de Physique' [3], vol. 10, p. 653, 1901.

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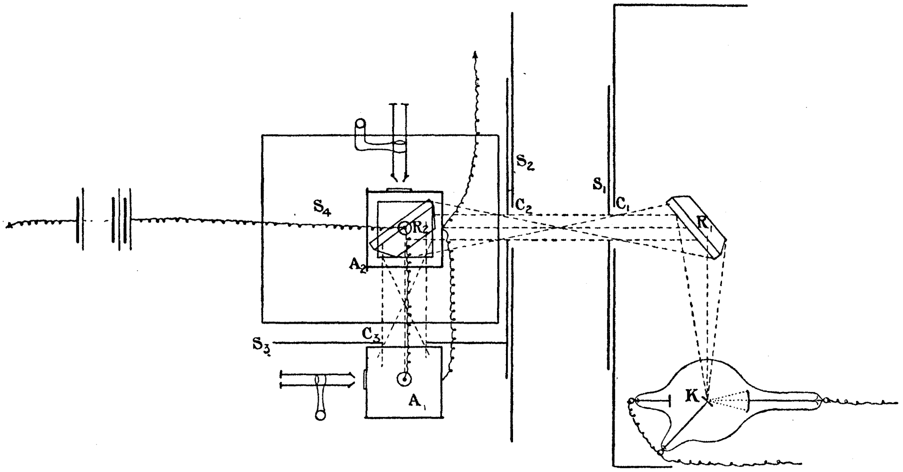
from the tube. This was so placed that the line (about 16 cm. long) joining the centres of the antikathode and the carbon plate was parallel to the side of the box. The size of the aperture C_1 was adjustable by lead shutters S_1 placed just outside. Large screens S_2 of thick sheet lead were placed at a distance of 10 cm. from these shutters and parallel to the side of the box, so that the width of the aperture between them was also adjustable. The secondary beam passing through the aperture C_2 was then the beam whose polarisation was to be tested. Beyond S_2, and in a vertical plane perpendicular to the screen S_2, was another screen S_3, containing a square aperture C_3 (5×5 cm.), distant about 12 cm. from the centre of the radiator R_2, situated in the secondary beam about 10 cm. beyond the screens S_2. No secondary radiation from R_1 was incident upon the aperture C_3, for it was screened from R_1 by lead plates as shown in the figure. But tertiary radiation proceeding from the radiator R_2 passed through the aperture C_3. The beam which entered the electroscope A_1,* through a thin paper and aluminium face placed immediately behind this aperture, consisted then of radiation whose direction of propagation was approximately horizontal and perpendicular to the direction of propagation of the secondary beam. A similar lead screen S_4, and a brass plate which supported another electroscope A_2, were placed in horizontal planes above the secondary beam in such positions that the centres of the apertures were vertically above the centre of the radiator R_2, and distant about 12 cm. from it. Tertiary radiation proceeding in a vertical



Plan of apparatus, showing position of bulb giving maximum deflection of electroscope A_1 and minimum of electroscope A_2.

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* For description, see paper on "Polarised Röntgen Radiation."

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direction from the radiator in the secondary beam, passed through the apertures and entered electroscope A_2 through a thin paper and aluminium face.

The charging rod of each electroscope was connected to one terminal of a battery of 150 Leclanché cells, whose other terminal was earthed, so that the insulated wire and gold-leaf of each could be charged by means of the contact-maker, which momentarily connected the rod and wire, leaving the wire and gold-leaf charged and insulated.

The normal leak in each electroscope due to the ionisation of air within the electroscope case was of course a much more considerable fraction of the total leak during the period of X-ray production than in the previous experiments on secondary radiation, and the rate of ionisation due to all causes was so small that the saturation current between the gold-leaf and electroscope case would have been obtained by a small fraction of the potential gradient here used.

In the lead box the Röntgen-ray tube was situated so that the line joining the centre of its antikathode to the middle of the radiator R_1 was approximately perpendicular to the line joining the mid points of apertures C_1 and C_2, and no primary radiation passed through the aperture S_2.

All the rays passing through S_2 were then secondary rays from R_1 and from air, and these set up a tertiary radiation in R_2 and the air in the neighbourhood, some of which passed through the electroscopes set in position to indicate relative intensities of this tertiary radiation.

The secondary and tertiary radiations from air were of course small in comparison with the similar radiations from the large masses of carbon R_1 and R_2. A few simple experiments showed that the ionisation occurring in the electroscopes beyond the normal was due, as was expected, almost entirely to radiation proceeding from R_2 and set up by radiation from R_1, *i.e.*, to tertiary radiation.

To show the conclusiveness of the experiments, these will be described in detail.

The rates of deflection of the gold leaves in both electroscopes were first determined when the X-ray tube was not excited. These gave the effects of the normal ionisation taking place within the electroscope cases.

A discharge was passed through the X-ray tube for a definite time and the deflections were again observed; it was found that the rates of deflection were considerably increased by amounts depending on the direction of propagation of the primary beam incident on R_1 as well as on the intensity of the primary radiation. Dissimilarities in the construction of the electroscopes made these rates of deflection not accurately proportional to the intensities in

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the two directions, but they were easily standardised by placing the X-ray tube in a position such that the primary beam was in a direction symmetrical with regard to the two directions, that is, making an angle of 45° with the vertical and horizontal tertiary beams studied.

It was soon seen that these increases in the rates of deflection were due almost entirely to the tertiary beams whose relative intensities it was desired to measure. By removing the radiator R_1, the rates of deflection became small again, showing that the effects of direct primary radiation through the screens, stray secondary radiation, tertiary radiation from air in the neighbourhood of R_2, etc., were small.

The radiation from R_1 was therefore the direct or indirect cause of the additional deflections.

By placing lead screens successively at apertures C_1 and C_2, and again observing the deflections during discharge when R_1 was in position, it was seen that the radiation directly or indirectly producing ionisation in the electroscopes passed through the two apertures, for the closing of these made the rates of deflection small again.

Finally, by removing the radiator R_2 it was proved that the deflections were not directly due to this secondary beam, but to a tertiary radiation proceeding from this radiator, for they became almost normal again; the tertiary radiation from air was of course small.

The X-ray tube was then turned about the axis of the secondary beam $R_1 R_2$, while the distance between the centres of the antikathode and radiator R_1 was unchanged. The radiator was so situated that the angle of incidence of the primary X-rays on it was unaltered when the primary beam KR_1 was turned through a right angle. This, though unnecessary in showing the relative variations in intensity of the two tertiary beams, made the results more convincing, for it showed independently the variations in these two beams due simply to rotation of the secondary beam.

As the X-ray tube was rotated in the manner indicated there was a considerable change in the intensities of the tertiary beams, one decreasing while the other increased. The horizontal tertiary beam reached a maximum in intensity when the primary beam was horizontal and a minimum when the primary was vertical; with the vertical tertiary the positions were reversed. Some of the readings obtained are shown in Table I, p. 252.

Experiments 1, 2, 3 and 4 showed the deflections of the electroscopes under conditions referred to previously when the tertiary radiations, which it was desired to measure, were not set up. Thus the normal deflection due to causes other than the tertiary radiations (principally normal ionisation and ionisation produced by the very penetrating radiation from the bulb through

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Table I.

Conditions of experiment.	Direction of primary beam.	Period of X-ray production.*	Readings and deflections of electroscope A_1 receiving horizontal tertiary beam.	Readings and deflections of electroscope A_2 receiving vertical tertiary beam.
1. Radiator R_1 absent	Horizontal	15 mins.	{16·5 18·5} 2	{50·2 51·5} 1·3
2. Lead screen at aperture C_1 ...	„	15 „	{10·8 12·6} 1·8	{43·5 44·9} 1·4
3. Lead screen at aperture C_2 ...	„	15 „	{18·7 10·4} 1·7	{55·7 57·2} 1·5
4. Radiator R_2 absent	„	15 „	{18·5 20·7} 2·2	{60·7 62·55} 1·85
5. Carbon radiators R_1 and R_2...	„	15 „	{18·7 26·9} 8·2	{51·4 54·8} 3·4
6. „ „ ...	Vertical	15 „	{28·6 32·3} 3·7	{56·6 64·4} 7·8
7. Carbon radiator R_1 and iron radiator R_2	„	15 „	{11·7 19·8} 8·1	{33·3 41·2} 7·9
8. „ „	Horizontal	15 „	{20 28·1} 8·1	{39·7 47·8} 8·1

* The discharge was actually passed for only half a minute in each of the 15 minutes, in order to keep the tube more constant.

the lead screens and electroscope cases) were approximately 1·9 and 1·5 in the two electroscopes.

These had to be deducted from the deflexions in experiment 5, in which carbon radiators were used. When the primary beam was turned through a right angle, the deflections changed from 8·2 and 3·4 to 3·7 and 7·8 respectively. The corrections applied to the readings given in the second position (Experiment 6) were found as above to be 1·75 and 1·95. After correction the true readings were—

Direction of primary beam.	Deflection of electroscope A_1 receiving horizontal tertiary beam.	Deflection of electroscope A_2 receiving vertical tertiary beam.
Horizontal......	6·3	1·9
Vertical.........	1·95	5·85

Thus the horizontal intensity changed from 6·3 to 1·95, while the vertical intensity changed from 1·9 to 5·85. These numbers show the variation exceptionally well, as owing to slight irregular motion of the gold-leaves the readings could not be obtained with certainty to less than about 0·3 of a scale division. At times, however, the variations were very small and consequently accurate readings were obtainable.

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The results are in striking contrast to those given by Experiments 7 and 8, in which the second radiator R_2 was of iron.

A number of experiments were made previous to those the results of which have been given. In these the sizes of apertures, the distance of the antikathode from the centre of radiator R_1 and other details were slightly different, but the possible error was not so small as in the later experiments. In every experiment however the same effect was clearly shown, the ratio of the intensities in the two principal directions being between 1 : 2·5 and 1 : 3·5.

The results of one of these are given below, as they show the deflections when the primary beam was horizontal, vertical and midway between the two. The preliminary experiments as shown above were not made, consequently the corrections were not accurately known. The numbers however show the kind of result that was obtained by a rough experiment without any special precautions.

Table II.

Conditions of experiment.	Direction of primary beam.	Period of X-ray production.	Readings and deflection of electroscope A_1 receiving horizontal tertiary radiation.	Readings and deflection of electroscope A_2 receiving vertical tertiary radiation.
Carbon radiators R_1 and R_2 ...	45° to vertical	15 mins.	$\left\{\begin{array}{l}24{\cdot}4\\30{\cdot}9\end{array}\right\}6{\cdot}5$	$\left.\begin{array}{l}14{\cdot}6\\20{\cdot}5\end{array}\right\}5{\cdot}9$
„ „ ...	Vertical	15 „	$\left\{\begin{array}{l}31{\cdot}4\\34{\cdot}5\end{array}\right\}3{\cdot}1$	$\left.\begin{array}{l}21{\cdot}2\\28{\cdot}8\end{array}\right\}7{\cdot}6$
„ „ ...	Horizontal	15 „	$\left\{\begin{array}{l}35{\cdot}6\\45{\cdot}9\end{array}\right\}10{\cdot}3$	$\left.\begin{array}{l}29{\cdot}2\\31{\cdot}8\end{array}\right\}2{\cdot}6$

These results were anticipated by a consideration of the theory of the production of secondary X-rays in carbon and other substances of low atomic weight.

When the direction of propagation of the primary beam was horizontal, the secondary radiation proceeding from the radiator R_1 in the direction $R_1 R_2$ was set up by the vertical components of electric displacement in the primary beam, consequently in the secondary beam the direction of electric displacement was vertical, and the intensity of tertiary radiation was therefore a maximum in a horizontal direction and zero in a vertical direction.*

As the beams studied were of considerable cross-section, the secondary here studied could not be completely polarised, for at any point there were superposed radiations proceeding in different directions from all the

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* This reasoning is based on the assumption that there is perfect freedom of motion of the corpuscles in the atom. Even in light atoms there must be inter-corpuscular forces brought into play, consequently polarisation cannot be absolutely complete.

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corpuscles in the radiator R_1. Nor, had there been complete polarisation of the secondary, could this have been detected by the study of tertiary beams of finite closs-section. Hence the ionisation in the electroscope receiving the vertical beam did not vanish, but reached a minimum.

The same reasoning applies to the case in which the direction of propagation of the primary beam was vertical, if we interchange the words vertical and horizontal. The variation in intensity of tertiary radiation in these experiments has been shown to be expressed approximately by the ratio 1 : 3. Thus the ratio of rates of ionisation in the two electroscopes changed from 6·3 : 1·9 to 1·95 : 5·85. Considering the obliquity of both secondary and tertiary rays in the beams studied, this is the order of result that might be expected if narrow pencils of radiation produced almost complete polarisation in the secondary.

To verify the dependence of the effect on the method of production of secondary X-radiation in substances of low atomic weight, and at the same time to obtain confirmation of the interpretation of these results, a metal plate of approximately the same area as the carbon was used as the second radiator R_2. Here again the choice of a substance was very limited, for while one was required that emitted a secondary radiation differing considerably from the primary (or in this case a tertiary differing from the secondary), it was impossible from the magnitude of the effects to sacrifice intensity. As in these experiments it was necessary to place the electroscopes at a distance of some centimetres from the radiator, the substance which emitted a radiation of such intensity and absorbability as to produce the maximum ionisation in the electroscopes at that distance was required. From a series of experiments it was found that iron was the most suitable.

The tertiary radiation from iron produced considerable ionisation in both electroscopes, but when the position of the tube was changed as before, no trace of the variation in intensities was detected. These results are shown by experiments 7 and 8 in Table I.

A number of observations were made in which, although there were changes in the intensity of primary radiation causing changes in the absolute values of the deflections, the ratio of these deflections remained constant within a few per cent. This is shown in Table III, p. 255.

This result, again, was what previous experiments on iron led one to expect.* It can be accounted for by considering the independence of motion of the corpuscles or electrons to disappear in the heavier atoms in which the systems are more complex. In these there is a much more

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* See previous paper.

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Table III.

Experiment.	Direction of primary beam.	Period of X-ray production.	Readings and deflections of electroscope A_1 receiving horizontal tertiary beam.	Readings and deflections of electroscope A_2 receiving vertical tertiary beam.	Ratio of deflections.
Carbon radiator R_1 and iron radiator R_2	Vertical	15 mins.	11·7 19·8 } 8·1	33·3 41·2 } 7·9	100 : 97·5
” ”	Horizontal	15 ”	20 28·1 } 8·1	39·7 47·8 } 8·1	100 : 100
” ”	Vertical	15 ”	19 26·3 } 7·3	21·3 28·3 } 7	100 : 96
” ”	Horizontal	15 ”	27·6 35·8 } 8·2	29·9 38·3 } 8·4	100 : 102·5
” ”	Vertical	15 ”	35·8 43·1 } 7·3	40·3 47·5 } 7·2	100 : 98·5

intimate connection between each corpuscle and its neighbours, and as a consequence each is subject to considerable forces during the period of passage of each pulse over a group of corpuscles in the neighbourhood, and the resultant acceleration is not in the direction of electric displacement in the secondary beam.* The difference in intensity of the tertiary in different directions hence disappears, while the pulse thickness in the tertiary beam becomes greater than in the secondary.

This experiment was perhaps the most conclusive proof of the interpretation of the results obtained with carbon, the essential point of difference in the two experiments being the substance of the radiator R_2. The order of magnitude of the ionisation produced was the same in the two cases, so that all other effects must have been equally prominent, yet the results were entirely different and may be fully explained from theoretical considerations of the processes taking place during the passage of Röntgen rays through different substances.

When the radiator R_1 was of iron and R_2 of carbon, the ionisation produced was too small to be measured. This is accounted for by the fact that the radiation from iron is much more readily absorbed, consequently only a very thin layer of carbon is penetrated by this radiation, and only a small mass is thus effective in producing tertiary radiation. A much greater fraction of the energy of secondary radiation is transformed into heat and less into energy of tertiary radiation.

We thus have evidence of a fairly complete polarisation in the secondary Röntgen radiation from carbon, and the theory of these radiations is further confirmed.

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* The subject will be more fully dealt with in a paper on "Secondary Radiation."