XXVI. *Note on X-Rays and Scattered X-Rays* *.

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IN a paper on Polarized Röntgen Radiation ‡ I showed that on the æther-pulse theory of Röntgen rays, we should expect the primary beam proceeding from an X-ray tube in a direction perpendicular to that of propagation of the cathode stream to be partially polarized, and on the theory of scattering by electrons in light atoms the secondary rays proceeding in a direction perpendicular to that of propagation of the primary, from substances of low atomic weight, ought to be almost completely plane polarized. Experiments were described which in both cases demonstrated the polarity§, and the effects were shown to be of the order of magnitude expected on these theories. The evidence in favour of the theories appeared so strong, that a more complete study of the distribution of intensity of the secondary radiation was considered unnecessary and unimportant. Prof. Bragg, however, in a recent paper || regards some of the evidence in favour of the æther-pulse theory as a little over-rated, and proposes in its place the hypothesis that an X-ray beam consists mainly of "neutral pairs" (each consisting of a positive and a negative particle rotating in a plane containing the direction of propagation of the "pair"). This he considers affords an easier explanation of the phenomena of X-rays and is not improbable *a priori*.

It appears altogether unnecessary to fully discuss such an hypothesis, for the study of the distribution of intensity of secondary radiation from light atoms affords a simple and apparently conclusive test between the æther pulse and the "neutral pair" theories. At the same time this makes the investigation on polarization more complete, and furnishes a delicate method of testing the presence of scattered rays in a complex radiation.

According to the æther-pulse theory of Röntgen rays, when a primary pulse passes over an electron in a light atom, the electron is accelerated in a direction opposite to (being charged negatively) the direction of electric intensity in the

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‡ Phil. Trans. A. vol. ccxiv. 1905, pp. 467-479.

§ Royal Soc. Proc. A. vol. lxxvii. 1906, pp. 247-255.

|| Phil. Mag. [6] vol. xiv. Oct. 1907, pp. 429-449.

pulse. During the passage of an unpolarized primary beam, these accelerations are uniformly distributed in direction in a plane perpendicular to that of propagation of the beam.

Now the electric intensity at a point P in one of the resulting secondary pulses is expressed by $\frac{ef \sin \theta}{r}$, where

e is the charge and f the acceleration of the electron, r the distance from the electron to the point P, and θ the angle which the line joining the electron to the point P makes with the direction of acceleration.

If P is on the line of propagation of the primary pulse over the electron $\theta = \frac{\pi}{2}$, and the intensity $= \frac{ef}{r}$.

If P is in the plane through the electron perpendicular to the direction of primary propagation, θ varies uniformly from 0 to π for the primary pulses.

The intensities of radiation then in these two directions are proportional to

$$\Sigma \frac{e^2 f^2}{r^2} \text{ and } \Sigma \frac{e^2 f^2 \sin^2 \theta}{r^2} \text{ respectively.}$$

When the primary beam is unpolarized, the average value of $\sin^2 \theta = \frac{1}{2}$, consequently the intensity of secondary radiation in the direction of propagation of the primary is double that in a direction at right angles.

On the neutral pair hypothesis it is supposed that a pair which strikes a substance consisting of light atoms is liable to be taken up only by an atom revolving in the same plane. It is sometimes ejected again, and its subsequent rotation and translation continue to take place in the one plane; therefore all pairs ejected in any direction at right angles to that of propagation of the primary rotate in the plane of primary and secondary propagations. A tertiary beam is therefore strongest when in the same plane. This is Bragg's explanation of the polarization of the secondary beam as shown by the tertiary beams.

The results of experiments described below, however, show that this cannot be the true explanation of the polarization effect; neither is the theory capable of explaining the partial polarization of the primary. It is easily seen that on this hypothesis all the possible planes of rotation of pairs in a primary beam contain the direction of propagation of that beam, and therefore that any pair has a chance of being

ejected again along that axis. If we consider the radiating mass at the centre of a sphere with the direction of primary propagation as the axis, then the different possible planes of ejection are the planes through this axis, and as in each plane we may assume there is equal chance of ejection in all directions, the number of pairs received by any element of surface of the sphere is proportional to the density of the lines of longitude on that element. This varies as the secant of the latitude from 1 at the equator to infinity at the poles. The total energy of radiation received by a small area near the poles is therefore many times as great as that received by a similar small area near the equator; that is, a small beam of secondary rays proceeding in a direction near that of propagation of the primary, is many times as intense as one in a direction approximately at right angles to this.

To test between these theories, the simple apparatus was arranged as shown in the diagram.

A narrow pencil of X-rays emerged through a small circular aperture of $\cdot 85$ cm. radius in a lead box, and at a distance of 38 centimetres in this pencil a square slab of carbon (8×8 cm.) was placed in a vertical plane with its face equally inclined to the lines joining its centre to the centres of two equally distant rectangular apertures A_1 and A_2 in lead screens. Behind these were situated electroscopes

of the type described in previous papers—modifications of those devised by C. T. R. Wilson. Their thin paper and aluminium faces were against the apertures, which were of dimensions 3.2×5 cm. and 5×5 cm., and were placed symmetrically with regard to the carbon at a distance of 27 centimetres.

With this arrangement the radiation from each atom before entering one electroscope had to travel approximately the same distance in carbon and air as that entering the other. The intensities of the secondary beams entering the electroscope were then proportional to the intensities of radiation from the atoms in the two directions RA_1 and RA_2 . One of these RA_1 made only a small angle with the axis of the primary beam, while the other RA_2 was perpendicular to that axis.

By first placing a sheet of copper in the position R, it was found, by alternately placing one electroscope in the two positions A_1 and A_2 , that there was no appreciable difference between the intensities of secondary radiation from copper in the two directions.

This is what was expected from the results of previous experiments on copper, for it was found that when a polarized primary beam fell on copper the intensities in the two principal directions at right angles were equal, indicating that the copper radiation was equally intense in all directions whatever the position of the plane of polarization and direction of incidence of the exciting primary beam. The character of the secondary radiation from copper had also been shown to be approximately independent of that of the primary producing it. The equally intense copper radiations were therefore used to standardize the two electroscopes afterwards used in place of the one.

Thus in one experiment after correction for the normal ionization in the electroscopes, for the effects of the secondary rays from air and for the ionization that may have been produced by very penetrating primary rays in the electroscopes, the deflexions of electroscopes A_1 and A_2 were 12.5 and 18.05 respectively when copper was the radiating substance. Now as these were due to equally intense beams, the deflexion of 12.5 in electroscope A_1 was equivalent to 18.05 in A_2 . When the copper was replaced by carbon the deflexions were 7 and 5.2 respectively, and by repeated observations 7.9 and 5.95. Taking the average of these we have 7.45 and 5.575. If the electroscopes had been equally

sensitive the ratio of deflexions would therefore have been

$$\frac{7.45 \times 18.05}{12.5} : 5.575.$$

$$i. e. \quad 10.76 : 5.575$$

$$\text{or} \quad \underline{1.93 : 1.}$$

That is, the average intensities of the secondary beams from R received by the electroscopes A_1 and A_2 were in the ratio 1.93 : 1.

As this ratio appeared to vary considerably in different experiments by an amount much greater than the possible experimental error would account for, it was apparent that it depended to a certain extent on the character of the primary radiation.

Gas was therefore admitted into a regulating X-ray tube, until it was brought to that state when a discharge through it did not produce X-rays which could be detected by the electroscopes at all. A discharge was then passed through until rays were emitted in sufficient intensity to be experimented upon. The ratio of intensities was then found to be 2.0 : 1. When the bulb was somewhat "harder" this became 1.93 : 1, and when "harder" still the ratio became 1.80 : 1. In order to experiment on a beam of much greater average penetrating power, the more absorbable portion of this beam was then cut off by a plate of aluminium .04 cm. in thickness. This diminished the ionizing power of the primary to about 30 per cent. of its original value, while the transmitted beam was on the average about twice as penetrating. Using this penetrating primary beam, it was found that the ratio of intensities had dropped to 1.51 : 1.

These experiments were repeated with other X-ray tubes and the results were confirmed, the ratio never exceeding 2 : 1, and decreasing with increasing penetrating power of the primary rays used.

It must, however, be observed that the primary beam used in these experiments was partially polarized, the variation in intensity of secondary beams from carbon in the two principal directions at right angles to the direction of primary propagation amounting to about 20 per cent. when the beam was of the very absorbable type, but only to 6 or 7 per cent.* when the rays were much more penetrating. Thus the

* There is, of course, probably no lower limit to the variation, but these were approximately the limits found for the different beams of the type used in these experiments.

intensity of the beam RA_2 depends to this extent on its position with regard to the cathode stream in the X-ray tube. The above ratios were obtained when the beam RA_2 was parallel to the cathode stream, and therefore have the maximum values. The intensities of secondary radiation in directions RA_1 and RA_2 when easily absorbed primary rays were used, were therefore in ratios varying from 2 : 1 to 2 : 1.2, *i.e.* from 2 : 1 to 1.66 : 1, according to the position of the plane of polarization of the partially polarized primary beam.

For an unpolarized primary beam, the ratio of intensities in the two directions RA_1 and RA_2 would therefore be approximately 1.85 : 1.

The results of these experiments in this way showed that the ratio of the intensities of secondary rays from carbon in the two directions indicated varied from about 1.85 : 1 with very soft rays to about 1.45 : 1 for penetrating rays. Now the first ratio is of the order—probably a little less—that might have been expected if we assumed perfect scattering on the æther-pulse theory, the rays entering electroscope A_1 making a small angle with the direction opposite to that of primary propagation, and most of those entering A_2 being not quite perpendicular to the direction of propagation of the primary.

On the other hand, on the neutral pair hypothesis the ratio should be roughly 7 or 8 : 1. This, however, is on the assumption that a pair rotating in one plane continues even after ejection from an atom which it strikes to rotate *accurately* in the same plane. If we admit any deviation from this, then the ratio of intensities becomes less than the above. But the polarization which exists in a secondary beam from carbon is sufficiently complete to show that if the effects are to be explained on such an hypothesis, the behaviour of the pairs must approximate very closely to this ideal, and consequently the ratio of intensities in the two directions RA_1 and RA_2 could not possibly have been lower than 4 : 1 or 5 : 1.

We thus have what appears to be most conclusive evidence against the “neutral pair” hypothesis, and the most convincing verification of the æther-pulse theory that could be given by such experiments.

Not only is there perfect agreement between theory and experiment here, but experiments showed that where the secondary rays were otherwise found to be less purely a scattered radiation judged by their penetrating power, and by polarization experiments, there was also a reduction of the ratio of intensities discussed in this paper—the result to be expected on the pulse theory.

Thus:—

Using the rays which are emitted by an X-ray tube in which the pressure is as high as possible when producing X-rays of appreciable ionizing power, the absorbability of the secondary rays from carbon differs exceedingly little if at all from the primary. Direct experiments did not indicate the slightest difference.

Using such a beam as the primary to be tested for polarization by study of the intensities of secondary radiation from carbon, the maximum amount of polarization of a primary was observed—about 20 per cent. variation. When such a primary was used to produce a secondary beam from carbon, the secondary beam was found by a study of the tertiary rays to be fairly completely polarized.

When such a primary beam was incident on carbon, the ratio of the intensities of secondary radiation in the direction opposite to that of propagation of the primary and in a direction at right angles was very close to the theoretical value for perfect scattering, *i. e.* 2 : 1 (within 5 per cent.).

As the primary rays became more penetrating, the difference in the ionizing powers of the primary and secondary beam from carbon became more marked; the difference in their penetrating powers increased; the evidence of polarization of the primary became less pronounced*; and the ratio of intensities of secondary radiation opposite to and perpendicular to the direction of primary propagation decreased.

According to this theory, then, all those substances of low atomic weight—up to and including sulphur—when subject to “soft” X-rays should emit secondary rays varying in intensity in the two directions approximately in the ratio 2 : 1. It is possible, I think probable, that the behaviour of sulphur varies much more rapidly with a variation of the penetrating power of the primary than any of the others, and that for some primary rays this ratio of intensities may be very different from that found by experiments on the lower part of this group.

Paper, when tested in the same way as carbon for “soft” rays, gave off radiation whose intensity was found to vary in the ratio 2·01 : 1, which again after correction shows the true ratio of intensities not appreciably different from that for the “softest” rays from carbon.

* This might possibly be due to the penetrating primaries actually being less polarized, but when considered with other changes it appears probable that much of the decrease of observed polarization is due to the secondary beams not consisting of purely scattered rays, and so not *showing* the polarization. The best results showing polarization in the secondary beam were always obtained by using easily absorbed rays.

Though accurate experiments were not made on aluminium, it was found to behave in the same way.

The penetrating power of the principal portion of the secondary radiation from Cr, Fe, Ni, Co, Cu, Zn has been found to be entirely different, being almost if not quite completely independent of the penetrating power of the primary producing it. The origin of the radiation will be discussed elsewhere. The intensity from one of these we should expect *not* to depend on the direction of propagation of the primary. This is what was found for the radiation from copper. When, however, the behaviour of iron was compared with that of copper, it was invariably found that the ratio for iron was greater than that for copper. This is shown below. The three comparisons were made at different times. It appears to indicate a small amount of scattered radiation, though possibly not more than 2 per cent. of the total radiation *from each atom*.

Radiator.	Time.	Corrected deflexion of A_1 .	Corrected deflexion of A_2 .	Ratio of deflexions $A_1 : A_2$.	Ratio of intensities of RA_1 and RA_2 .
Cu	40 secs.	22.3	29.8	75 : 100	1 : 1
Fe	25 "	12	14.25	84 : 100	1.12 : 1
Cu	40 "	27.5	42.45	65 : 100	1 : 1
Fe	50 "	27.7	37.15	74 : 100	1.13 : 1
Cu	75 "	34.2	48.8	70 : 100	1 : 1
Fe	75 "	26.7	34.55	77.2 : 100	1.10 : 1

It seems quite possible from other considerations that a certain amount of scattered radiation does appear, as the atomic weight is getting near that for which a scattered radiation was found by much cruder methods.

Again, Ag, Sn, Sb, I, &c. belong to quite another class of substances, for the radiation from these depends to an extraordinary extent upon the character of the primary. It has been shown that when primary rays of moderate penetrating power are used, this secondary is not a scattered radiation, though from tin its average penetrating power may be very like that of the primary producing it; it is not polarized, and it does not give evidence of polarization in a primary where it exists. Though very different from the radiation from one of the elements in the Cr-Zn group, we should for these reasons expect the beam to show very little or no variation in intensity in the beams RA_1 and RA_2 . The results of comparisons with copper are given.

Radiator.	Time.	Corrected deflexion of A_1 .	Corrected deflexion of A_2 .	Ratio of deflexions of A_1 and A_2 .	Ratio of intensities.
Cu	60 secs.	33.32	60.67	54.9 : 100	1 : 1
Sn	180 „	6.27	12.15	52.4 : 100	.95 : 1
Cu	50 „	23.6	38.8	60.8 : 100	1 : 1
Sn	180 „	6.65	10.5	63.3 : 100	1.04 : 1
Cu	40 „	27.5	42.45	65 : 100	1 : 1
Sn	240 „	13.6	20.5	66.3 : 100	1.02 : 1

From these experiments there was no indication of a decided variation; we conclude that there was equality of intensity in the two directions. Another group of substances classified according to their behaviour under X-ray transmission includes W, Pt, Pb, and Bi. These emit a radiation which appears to differ from that from any of the other groups referred to. When the radiation from lead was tested in a similar way, no evidence of scattering was obtained.

Experiments were also made to determine the behaviour of a number of these elements under more penetrating rays, but the conditions of experiments have not yet been varied sufficiently to lead to definite conclusions.

These results thus afford strong confirmation of the electromagnetic pulse theory of X-rays, and of the theories of scattering and of polarization based on this.

The method of comparing the intensities of radiation in the two directions indicated is a delicate one for detecting the presence of scattered rays, or of measuring the control over radiating electrons, exercised by the primary pulses while producing or stimulating the production of secondary rays.

The scattering of "soft" X-rays by substances of low atomic weight has been shown to be almost perfect, and the appearance of a radiation which is very far from a purely scattered radiation, when more penetrating rays are used, has been shown in a very marked way. The small proportion of scattered rays in other secondary radiations has been demonstrated.

These experiments, however, do not show that under suitable conditions scattered rays may not be obtained from elements hitherto found to emit only an uncontrolled secondary radiation.

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