

LXI. *Energy of Secondary Röntgen Radiation.* By CHARLES G. BARKLA, M.Sc. (Vict.), B.A. (Cantab.), King's College, Cambridge; Oliver Lodge Fellow, University of Liverpool*.

IN a paper on "Secondary Radiation from Gases subject to X-rays" † experiments were described which led to the following conclusions:—

All gases subject to X-rays are a source of secondary radiation, the nature of which is similar to that of the primary radiation. The absorbability of the secondary radiation is (within the limits of possible error—about 10 per cent. of the absorption coefficient for aluminium) the same as that of the primary radiation producing it.

For a given primary radiation the intensity of secondary radiation from different gases at the same pressure and temperature is proportional to the density of the gas from which it proceeds.

The opinion was expressed that the secondary radiation is due to a kind of scattering of the primary by the corpuscles constituting the molecules of the gas.

Results similar to those which led Sagnac‡ to conclude that the secondary radiation from air was more absorbable than the primary radiation producing it had been obtained, but the evidence was then considered insufficient to lead to a definite conclusion as to the difference in character of the two radiations. A direct method of comparison did not indicate the slightest difference in the absorption of the primary and secondary radiations by similar plates of aluminium.

As the experiments of Townsend§ and Sagnac|| on secondary radiation from metals showed that this radiation was more absorbable than the primary radiation producing it—the change in penetrating power, however, depending on the metal—and as the results referred to led to the probability of a transformation of the radiation by air, further and more careful experiments were made on the subject.

The following method was employed:—

A beam of X-rays passed through rectangular apertures in two parallel lead screens A and B (see figure). Two screens, C and D, were placed in planes perpendicular to the others,

* Communicated by the Physical Society: read March 25, 1904.

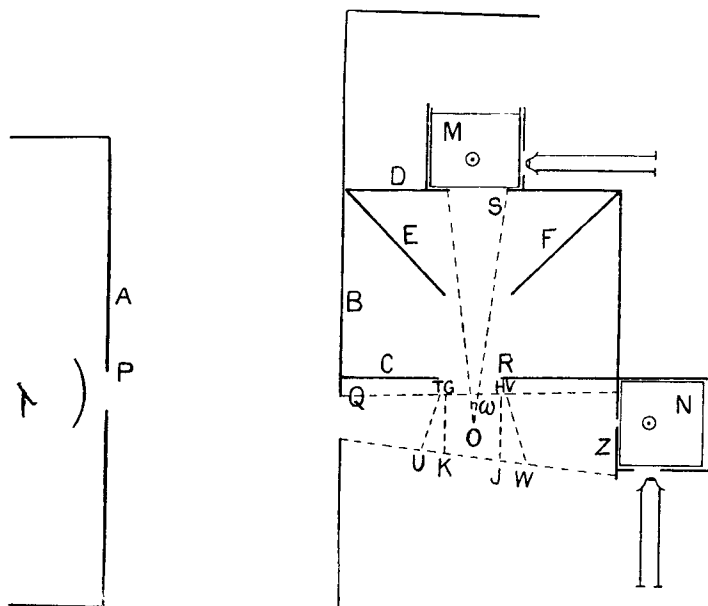
† C. G. Barkla, *Phil. Mag.* [6] v. p. 685 (1903).

‡ *Comptes Rendus*, cxxvi. pp. 521–523 (1898).

§ *Proc. Camb. Phil. Soc.* x. p. 217 (1899).

|| *Comptes Rendus*, cxxv. p. 942 (1897).

in positions shown in the figure, the screen C being just outside the primary beam and D parallel to C at a distance of 15 centimetres.



In C and D were two square apertures, R and S, 5 cm. sq., placed so that the lines joining corresponding points of the two were perpendicular to their planes.

Behind the aperture S was placed an electroscope M* which was carefully shielded from radiations proceeding from all directions except through the two apertures R and S. This radiation entered by a thin paper and aluminium window. Lead plates E and F protected it from secondary and tertiary radiation from metals. The rate of fall of the gold-leaf in electroscope M was then only affected by secondary radiation from air in the primary beam opposite aperture R.

A second similar electroscope N was placed behind thick leaden screens Z in the primary beam, and received a narrow pencil of primary radiation through a small hole in this screen. Absorbing plates could be placed immediately in front of both electroscopes. The rays then entered the primary electroscope N by passing normally through the absorbing plate. The secondary rays of greatest obliquity entering the electroscope M, in their passage through the

* For description see previous paper.

plate suffered absorption which would be produced by going normally through a plate of thickness $t(1.106)$, t being the actual thickness of the plate.

The average effective thickness of the plate was not more than $1.03t$. To compare the absorbability of the secondary rays with that of the primary, the ratio of the deflexions of the two electroscopes, consequent upon the ionizations produced in these electroscopes by the primary and secondary radiations, was first obtained. From the observation of the deflexion of one of these, the deflexion of the other could then be calculated to within about 3 per cent.

Plates of aluminium of equal thickness were then placed before the electroscopes, so that both the primary and secondary beams suffered absorption by transmission through aluminium. The ratio between the two deflexions consequent upon the passage of the primary and secondary beams through the electroscopes was again determined. In measuring the deflexions, corrections were always made for the result of the normal ionization taking place in the electroscopes. Many experiments were made with rays differing in penetrative power. In some of these the possible error was very small, and they showed that within 4 or 5 per cent. the absorption coefficients for the primary and secondary radiations were the same. Some of the results are given in Table I. (p. 546).

In the second, third, and fourth sets of experiments given in the table, the order of magnitude of the absorption may be seen from a comparison of the duration of experiment and deflexion of the primary electroscope in each case.

A sheet of aluminium of .04 cm. thickness reduced the rate of ionization in the electroscope by about 60 per cent.

In the first set the intensity of radiation was altered in the different experiments, so that the duration of experiments was varied little. The ionization in an electroscope was diminished by about 40 per cent. by a sheet of aluminium of .02 cm. thickness.

From the results given in the fifth column, it will be seen that in each case the rate of ionization in the secondary electroscope was diminished by the aluminium plate slightly more than that in the primary electroscope. But the effective thickness of the plate before the secondary electroscope was probably between 2 and 3 per cent. greater than that before the primary, so that the actual difference in the absorptions must have been exceedingly small if any difference existed.

Corrections have been made for the normal ionization in each electroscope.

TABLE I.

Conditions of Exp.	Duration of Exp.	Deflexion of Primary Electroscop.	Deflexion of Secondary Electroscop.	Ratio of Secondary Deflexion to Primary Deflexion.
Without absorbing plates	minutes.			
2 sheets of .01 cm. Al before each electroscop	24	31.05	10.6	34.1 to 100
Without absorbing plates	28	31	10.45	33.7 to 100
Without absorbing plates	26	30.4	10.5	34.5 to 100
Without absorbing plates	21	34.75	10.3	29.6 to 100
Sheet of .04 cm. Al before each electroscop	50	30.4	8.15	26.8 to 100
Without absorbing plates	30	34.6	9.7	28 to 100
Without absorbing plates	25	29.05	11.3	38.9 to 100
Sheet of .04 cm. Al before each electroscop	40	19.5	7.5	38.4 to 100
Without absorbing plates	30	23.75	9.5	40 to 100
Without absorbing plates	25	26.7	11.6	43.4 to 100
Sheet of .04 cm. Al before each electroscop	46	20.1	8.45	42.4 to 100
Without absorbing plates	20	21.2	9.2	43.4 to 100

In order to test this equality in penetrative power for rays differing enormously in character from those previously dealt with, experiments were made with secondary radiation from metals to get a secondary beam of sufficient intensity to use as a primary in experiments similar to those described. The radiation from copper was found to be sufficiently intense to use as a primary beam, as its great ionizing power in some degree compensated for the weakness of the radiation. It was, however, impossible to adopt the method employed with the more intense primary beams, as the ionization produced by what was in this case a tertiary radiation in electroscop M, in the position shown in the figure, was only a small fraction of the normal ionization when the electroscop was not in the path of any known radiation. Instead of placing the electroscop M so far away from the primary beam in

order to get the rays normal to the absorbing plate, and so greatly diminishing the energy of secondary radiation entering the electroscope, it was put immediately behind the aperture in screen C. The effective thickness of the absorbing plate was then much greater than before, as most of the radiation passed through it in a direction making a considerable angle with the normal. Before any accurate results could be obtained of the absorption of this secondary radiation, it was necessary to determine the effective thickness of the plate.

First using a primary beam consisting of rays of moderate penetrative power, such as had been experimented upon previously, it was possible, by comparing the rates of ionization in electroscope M when no absorbing plates were used, when an aluminium plate was placed in the primary beam by aperture P, and when the same plate was placed in front of the electroscope, to calculate, on the assumption that the beam was homogeneous in character, the effective thickness of a plate placed before the secondary electroscope. By using thin plates, the error due to the primary beam being a mixture of radiations differing in character was reduced to a minimum.

To obtain the very absorbable primary beam a copper plate was placed in the induction-coil box opposite the aperture, with the X-ray bulb as close as possible without emitting any direct radiation through the aperture Q. The secondary radiation from copper then constituted the new primary beam, and the tertiary radiation from air was the new secondary radiation. The boundaries of this primary beam were approximately the same as before, so that, neglecting the small error due to want of homogeneity, the effective thickness was as before. From the diminution in the rate of ionization in M when an absorbing plate was put at P, the corresponding diminution when the plate was placed at R was calculated on the assumption that the secondary and primary radiations again had the same penetrative power. This was then compared with the actual absorption produced by the plate at R.

As this test would only hold with accuracy provided the primary and secondary beams consisted of rays of one character, the thickness of the absorbing plate at P which produced the same absorption as a plate of given thickness at R was determined experimentally for the moderately penetrating rays, and the same comparisons were made as before.

This method was still open to the objection that the effective thickness of the plate at R determined experimentally for rays coming direct from an X-ray bulb was not the same as

that for a primary beam coming from a copper plate, for the radiation from metals is more heterogeneous than the primary radiation producing it. The two methods, however, would give different results if want of homogeneity affected them to an appreciable extent.

Both experiments gave within the limits of possible error the same absorption for the secondary as for the primary, showing that even for these very easily absorbed rays, the character of the secondary radiation differs little from that of the primary producing it.

The possible error was in this case naturally much greater than in the previous experiments, and amounted to fully 15 per cent. of the absorption coefficient.

Comparisons were then made between the rates of ionization produced in the two electroscopes when neither primary nor secondary beam was intercepted by absorbing plates, when similar aluminium plates were placed in the primary and secondary beams just before the electroscopes, and when an aluminium plate was placed in the primary beam at the aperture P. As stated previously, the same ratio was given (1) when no plate intercepted either beam as (2) when plates of equal thickness were placed before each electroscope. (3) When a plate was placed in the primary beam at P, the ratio of the rates of ionization in the two electroscopes secondary to primary was increased.

In these experiments the ratio was increased by about 10 per cent. when an aluminium plate .04 cm. thick was placed at P. This plate reduced the ionization in the primary electroscope to about 36 per cent. of its initial value, while the ionization produced by the transmitted radiation was reduced to about 54 per cent. by a second similar plate.

Experiments (1) and (3) showed that the rays which got through the aluminium produced a greater proportional secondary effect than the whole direct primary beam. This result must have been due either to a change in the intensity or in the character of the primary beam in its passage through aluminium. There was a possibility that the intensity of secondary radiation was not proportional to that of the primary radiation, even though the radiations were of the same character; and thus that the diminished intensity accounted for the proportional increase in the ratio of secondary to primary ionization. A given bulb was therefore worked in very different ways, currents of various strengths being passed through, so that in some cases the intensity of radiation was four or five times that in others. The differences in penetrative powers in the different experiments were small.

It was found that the ratio of the rates of ionization was practically the same in each case, showing it to be independent of the intensity of primary radiation.

The increase in the ratio of secondary to primary ionization by placing an absorbing plate at P was therefore due to the change in the character of the primary radiation by transmission through the plate. But it was shown to be independent of the position of the plate in the primary beam, as the ratio was unaltered when the plate was moved from P to Q. Hence the effect of secondary radiation from aluminium was negligible.

The conclusion was then that the rays of higher penetrating power produced a greater secondary ionization in proportion to the primary ionization produced by them than the more absorbable rays. This, again, could not have been due simply to scattering of these constituents in different proportions, for the results of experiments (2) and (3) would then have been identical. We thus arrive at the conclusion that there must have been a greater transformation* of the penetrating than of the more absorbable rays, the increase in ionizing power accounting for the proportional increase in the secondary ionization.

It should be noticed that experiments (2) and (3) do not in any way give a comparison of the absorption of the primary and secondary beams. If the primary beam were homogeneous in character, *i. e.* consisted of rays of one penetrating power, then the ratio of the secondary ionizations in the two cases would be the ratio of the fractions of primary and secondary radiations transmitted by a plate of the thickness used. Such a test would, however, be no more delicate than that given by experiments (1) and (2). If the different constituents of the primary beam were transformed equally, then again this test would be no more delicate than that given by (1) and (2).

The result depends merely on the difference in the transformation of the penetrating and of the more absorbable rays.

If the absorption by aluminium of different radiations were proportional to the ionization produced by these radiations in a given volume of air, then the absorption by aluminium would have been easily measured.

We thus conclude that for the rays experimented upon a

* The measure of transformation used is the ratio of the ionization produced in a given volume of air by the transformed beam to that produced by the primary beam if of the same intensity. This is not the ratio of the absorption coefficients for the rays by air, as the total absorption is not proportional to the ionization, but it is the ratio of what may be called the ionizing powers.

variation in the absorption by aluminium is accompanied by a much greater proportional change in the ionizing power in air.

As it was evident that there was a greater transformation of the more penetrating rays, further experiments were made to detect if possible a difference in the absorption of the secondary rays produced by a primary beam of intensely penetrating rays, and of the primary rays themselves, by plates of aluminium of equal thickness. As the average penetrating power of the radiations from different bulbs used did not differ sufficiently, one bulb was used, and the more absorbable rays were cut off by plates of aluminium. As the intensity of the primary and secondary beams was considerably reduced and the percentage possible error consequently increased, the accuracy of the former experiments was not attained. These experiments, however, seemed to indicate a slightly greater absorption of the secondary radiation than of the primary.

Having proved the approximate equality in penetrative powers of the primary and secondary radiation from air, it became a simple matter to investigate the relation between the energy lost in secondary radiation by a primary beam in its passage through air and the penetrating power of that radiation. The apparatus was arranged as shown in the figure, but with plates C and D much nearer. The ratio of the rates of deflexion of the secondary and primary electroscopes was determined for a given bulb in a fixed position when the current through it was varied, also when the bulb was soft and when hard. The ratio of secondary to primary ionization was apparently slightly greater for the penetrating than for the more absorbable rays. To obtain a beam of very absorbable rays the secondary radiation from copper was again used as the primary. A copper plate was placed as nearly as possible in the position previously occupied by the anticathode of the bulb, so that the boundaries of the beam were approximately the same as before. This was not obtainable with perfect accuracy, because in the former case the radiation had proceeded from practically a point source, while to obtain a beam of sufficient intensity from the copper, a plate several square centimetres in size was used. The difference in the two cases was, however, not considerable. The ratio of secondary to primary ionization was again determined, and was found to be of the same order as when the direct beam from the bulb was used as the primary.

The actual readings obtained are given below, but as the ionization produced in the secondary electroscope was only of the same order of magnitude as that occurring under normal conditions, the possible error was great.

TABLE II.

Primary Radiation in Experiment.	Duration of Experiment.	Primary Electro-scope Deflexion.	Secondary Electro-scope Deflexion.
Rays direct from bulb	minutes. 1·3	164·6	8·9
Secondary rays from copper ...	50	34·4	3·8
None	60	2·4	1·8
Rays direct from bulb	·5	187	7·5
Secondary rays from copper ...	60	71	5·5
None: screened by lead plate...	40	1·4	1·4

After correction for the normal ionization, and for absorption of the secondary rays from copper in their passage from aperture R to electroscope N of the order of 10 per cent., these readings were :—

Primary Radiation.	Ratio of Primary to Secondary Electro-scope Deflexion.
Rays direct from bulb	100 to 5·4
Secondary rays from copper	100 to 6·4
Rays direct from bulb	100 to 4
Secondary rays from copper	100 to 4·4

As the boundaries of the beam proceeding from copper were necessarily not so well defined as those of the beam direct from the bulb, on account of the much greater area of the source of radiation, the two were not accurately compared, so that the agreement between these results is quite as close as could have been expected. Quantitative results were thus obtained, showing that the secondary radiation from copper is of the same nature as the primary radiation, for the secondary radiation is productive of a tertiary radiation whose intensity bears the same relation to the intensity of the secondary as that of a secondary from air bears to the intensity of the primary producing it.

It has been shown that the intensely penetrating rays transmitted through sheets of aluminium give a slightly higher ratio of secondary ionization to primary ionization than the more absorbable radiation; and that this result is due principally, if not entirely, to the greater difference in ionizing power

between the secondary and primary radiations when penetrating rays constituted the primary beam than when it consisted of more absorbable rays. It is not due to a greater fraction of the energy going as secondary radiation.

We are thus led to the conclusion that—

The energy of secondary radiation from a definite mass of air through which a primary beam of uniform intensity passes is a definite fraction of the energy of the primary beam, whatever be the penetrative power of the primary radiation; or the intensity of secondary radiation depends on the intensity of the primary radiation, but not on the character of that radiation. This verifies the theoretical result given by J. J. Thomson ('Conduction of Electricity through Gases,' p. 271).

Energy of Secondary Radiation.

In the passage of Röntgen radiation through gases, part of the energy of this radiation is spent in the production of ions and subsequently appears as heat in the gas when the ions recombine, part appears more directly as heat, and part is productive of secondary radiation. The approximate proportionality between the absorption and the ionization led to the assumption that practically all the energy was spent in the work of ionization; but the experiments of H. A. Wilson * and of Townsend together with those of Rutherford and McClung †, giving the energy required to ionize a molecule and that absorbed per molecule ionized respectively, lead to the conclusion that only a small fraction of the energy absorbed is spent in the work of ionization. The energy of secondary radiation has been regarded as negligible. The experiments described show that the secondary radiation from gases differs little in absorbability from the primary radiation. It is hence an easy matter to compare the intensities of the secondary and primary radiations, for these are proportional to the ionizations produced by them in equal volumes of the same gas through which they pass, and hence the total energy of secondary radiation may be compared with that of the primary.

The electroscope used to measure the intensity of the secondary radiation was placed behind a square aperture 5 cm. by 5 cm. in a lead screen, in such a position as to receive the secondary rays proceeding from the air in a direction approximately at right angles to the direction of propagation of the primary rays (fig. p. 544).

* Phil. Trans. A. 197, p. 415, (1901).

† Phil. Trans. 196, p. 25 (1901).

The solid angle subtended by this aperture at the centre of the source of secondary radiation distant about 18·5 cm. was approximately

$$\frac{5^2}{(18\cdot5)^2} = \left(\frac{1}{3\cdot7}\right)^2 = \omega \text{ say.}$$

Evidence was given in a previous paper leading to the theory that this radiation has its origin in the charged corpuscles constituting the molecules during the passage of X-rays through the gas. The perturbations of these charged corpuscles by the strong electric field in the Röntgen pulses are in directions perpendicular to that of propagation of the primary rays, and the intensity of secondary radiation proceeding from a single corpuscle is different in different directions, being expressed by

$$\frac{1}{4\pi} \frac{e^2 f^2 \sin^2 \theta}{V \cdot r^2} *,$$

e being the charge on the corpuscle, f the acceleration of that corpuscle, V the velocity of light, r the distance of the point considered from the corpuscle, and θ the angle between the line joining these two with the direction of acceleration of the corpuscle.

The rate at which energy is radiated from the corpuscle is

$$\frac{2}{3} \frac{e^2 f^2}{V} \dagger,$$

Consequently the energy received by a small area subtending a solid angle ω' at the corpuscle =

$$\frac{3\omega'}{8\pi} \sin^2 \theta \text{ of the total energy of secondary radiation proceeding from that corpuscle.}$$

Now, as the electric displacements in the Röntgen radiation are in all directions perpendicular to the direction of propagation, and neglecting partial polarization of the primary beam ‡, if the line joining the small area to the source of secondary radiation be in the plane of electric displacements, the energy received by this area =

$$\frac{3\omega'}{8\pi} \cdot \frac{1}{2} \text{ of the total energy of secondary radiation}$$

proceeding from that corpuscle (the average of $\sin^2 \theta$ being $\frac{1}{2}$).

* J. J. Thomson, 'Conduction of Electricity through Gases,' p. 269.

† Through an error in integration this is given as $\frac{1}{3} \frac{e^2 f^2}{V}$ in 'Conduction of Electricity through Gases.'

‡ C. G. Barkla, Nature, March 17, 1904.

The energy of secondary radiation passing through the secondary electroscope was therefore

$$\Sigma \frac{1}{2} \cdot \frac{3}{8\pi} \omega' \cdot E_x,$$

the summation being over all elements of the aperture and all the corpuscles which contribute to the radiation through that aperture.

The effect of radiation from the air in the space G H J K is approximately the same as if all the corpuscles in that space radiated from the central point O. The angle subtended by aperture S at any corpuscle in the outer space shown in the figure depends on the position of the corpuscle, varying from ω just outside the space G H J K to zero at the outer boundaries of T U V W.

A calculation giving a result which can only be regarded as approximate, showed the total effect to be equivalent to that of all the corpuscles in a volume of air equal to about 194 c.c. radiating from O.

Therefore the energy of secondary radiation passing through electroscope M

$$= \frac{3}{16\pi} \omega E \simeq \frac{1}{230} E,$$

E being the total energy of secondary radiation from 194 c.c. of air.

The intensities of the primary and secondary beams were compared by using apertures of various sizes for the primary and secondary electroscopes, and comparing the areas of the two apertures which gave the same rate of leak in similar electroscopes. The intensities of radiation were then inversely as the areas of the apertures. As the electroscopes were not exactly similar they were standardized by finding the rate of leak produced in each by a beam of given cross section and intensity. The proportionality between the ionization produced in a given electroscope and the area of the aperture through which the beam was admitted was verified, so that local effects, as of a small portion of the beam being intercepted by the gold-leaf itself, were negligible.

The result was

$$\frac{\text{Intensity of Sec. Beam at S}}{\text{Intensity of Prim. Beam at R}} = 0.0000816$$

$$\therefore E = 0.0000816 \times 230 \times \{\text{Energy of Primary Beam of same cross section (5}^2 \text{ cm.)}\}$$

Now the length of the primary beam passing through

air and of cross section 25 sq. cm. giving rise to this secondary radiation

$$= \frac{194}{25} = 7.8 \text{ cm.}$$

Hence the energy of secondary radiation proceeding from 1 cm. length of the primary beam passing through air at atmospheric pressure and about 15° C.

$$= \frac{.00000816 \times 230}{7.8}$$

$$= .00024 \text{ of energy of primary radiation passing through.}$$

We thus see that the energy lost by secondary radiation is a considerable fraction of the total absorption, which is of the order .001 of the energy of the primary beam per centimetre.

As this radiation is most intense in the direction of propagation of the primary radiation, the primary beam is reinforced by a portion of the secondary so that the total loss of intensity of a beam whose breadth is not small in comparison with its length is not so much as indicated above.

It was shown in the previous paper that the energy of secondary radiation is proportional to the density of the gas through which the primary beam passes. When we take into consideration the loss of energy due to this secondary radiation, a considerable fraction of the absorption coefficients is accounted for and the ratio of ionization produced to absorption proper (neglecting the absorption due to secondary radiation) is more nearly a constant than the values given by Rutherford show. I think that the variations from this were all within the limits of experimental error*.

The close agreement between the ratio of absorptions found by Rutherford and the ionizations found by J. J. Thomson † for carbonic acid gas and air is accounted for by the fact that for the gases named, the ionizations for a given radiation are proportional to the densities of the gases. But the energy of secondary radiation is also proportional to the density of the gas, hence the sums of the energies lost in ionization and by secondary radiation are in the same ratio.

We thus find that the energy of Röntgen radiation lost by secondary radiation from gases at atmospheric pressure and temperature is very large compared with the energy lost in the work of ionization.

From the results of experiments of Townsend and H. A.

* Phil. Mag. [5] xliii. p. 241 (1897).

† 'Conduction of Electricity through Gases,' p. 251.

Wilson with those of Rutherford and McClung, J. J. Thomson* concluded that about $\frac{1}{80}$ of the energy of the rays is expended in the ionization of the gas, the rest being converted into heat. We see, however, that a large fraction—for moderately absorbable rays of the order $\frac{1}{4}$ —goes in secondary radiation. In the case of very penetrating rays the fraction is much larger.

J. J. Thomson has shown that if Röntgen radiation passes through a medium in which there are N ions per cubic centimetre each of mass m and possessing a charge e , then the radiation from each ion as its motion is accelerated by the intense electric fields in the Röntgen pulses, produces a diminution in the energy of the primary radiation, the rate of change of intensity of the primary beam due to this secondary radiation alone being given by the expression

$$\frac{dE}{dx} = -\frac{8\pi}{3} \frac{Ne^4}{m^2} E,$$

E being the intensity of primary radiation and $\frac{dE}{dx}$ the rate of change of intensity.

Now it was experimentally shown that the radiation was independent of the ionization in the gas from which the secondary radiation proceeded, but was proportional to the number of corpuscles or electrons in a given volume of the gas, and hence it was concluded that the corpuscles constituting the molecules were the sources of secondary radiation. Sub-

stituting the values experimentally determined for $\frac{dE}{E dx}$ in the above equation, together with the accepted values of e and m , we may calculate on this theory the number of corpuscles per cubic centimetre of air at atmospheric pressure and temperature, and compare this with the number assigned by the electronic theory of matter.

Taking $\frac{e}{m} = 7 \times 10^6$ and $e = 10^{-20}$,

$$\frac{dE}{dx} = -4 \times 10^{-26} NE.$$

But by experiment $\frac{dE}{dx} = -\cdot 00024 E$,

$$\therefore N = \cdot 6 \times 10^{22}.$$

Considering the range of possible values of e and m , there is a close agreement between the number thus obtained and

* 'Conduction of Electricity through Gases,' p. 255.

that calculated on the electronic theory of matter from the determined values of the number of molecules per cubic centimetre.

The number of ions (here denoting a molecule + or — an electron) necessary to produce the intensity of radiation experimentally determined would be between 10^{30} and 10^{31} per cubic centimetre. This is approximately 10^{11} times the actual number of molecules.

Quantitative measurements thus support the theory that the constituents of the molecules are the radiators.

The laws governing the secondary radiation from gases are thus in perfect agreement with the theory that this radiation proceeds from the negative corpuscles or electrons during the acceleration of their motion by the intense electric fields in the Röntgen pulses passing through the medium containing them.

No quantitative measurements of value have previously been made on the radiation from solids.

An experimental determination of the energy of secondary radiation proceeding from a brass plate which totally absorbed a primary beam was made by H. S. Allen*. He found that the number of ions produced in sulphuretted hydrogen by the secondary rays from brass was about $\frac{1}{2000}$ part of the number which would have been produced by the primary beam if it had been totally absorbed by the gas. This result has no special significance regarding the amount of transformation into secondary radiation, as an unknown fraction—but a very large one—of the total energy of secondary radiation was absorbed by the metal itself and transformed into heat. Only by using very thin sheets can an approximation be made to the fraction of the energy used up in the production of secondary radiation, or even to the character of the radiation proceeding from the metal. Sheets of metal of greater thickness give secondary beams of greater average penetrative power, for the deeper layers are only reached by the penetrating rays, and the most penetrating secondary rays penetrate to the surface in greatest proportion. Consequently the addition of more layers of metal results in the superposition of simply the most penetrating secondary rays, and the composition of the radiation proceeding from a thick plate is thus entirely different from that which is set up in each layer.

To measure the energy of secondary radiation from a solid, the radiation from which differed little in character from that

* Phil. Mag. [6] iii. p. 126 (1902).

of the primary, the same method was employed as has been described for air.

A sheet of paper weighing .373 gr. was placed in the primary beam with its plane inclined at an angle of 45° with the direction of propagation of the primary rays and with the line joining corresponding points of the two apertures R and S. The paper was so placed that the primary beam entering electroscope N was not intercepted by it. The absorption of the secondary radiation by plates of aluminium was, within 2 or 3 per cent., the same as that of the primary radiation, showing that the difference in character between these radiations was exceedingly small. The energy of secondary radiation was then compared with that proceeding from air. Correction was made for the absorption of primary and secondary radiations in the paper. The absorption produced by a sheet of paper of the same material and thickness as that used in the experiment amounted to about 7 per cent. of the energy of the radiation normally incident upon it. There was also a small correction made for the absorption of part of the secondary radiation from air which passed through the paper.

The results are given below :—

Secondary Radiator.	Ratio of Secondary Elec. Deflexion to Deflex. of Primary Electroscope.
.373 gr. paper	38.9 to 100
194 c.c. of air at 74 cms. press. and 17° C. (.239 gr.)	25.3 to 100

Correcting for absorption in the paper :—

$$\frac{\text{Energy of sec. radiation from .373 gr. paper}}{\text{Energy of sec. radiation from .239 gr. air}} = \frac{42.8}{25.3}$$

This gives as the ratio of the energies of secondary radiation from equal masses of paper and air 113 to 110. These are as nearly equal as the possible errors in estimating the volume of air productive of secondary radiation and in the electroscope deflexions admit.

We thus arrive at the conclusion that the energy of radiation from gases and light solids, the radiation from which differs little from that of the primary producing it, is for thin layers of equal thickness proportional to the density of the substance; that is, for radiation of given intensity the energy lost in secondary radiation is proportional to the quantity of matter passed through.

Recent experiments on secondary radiation proceeding from thin sheets of metal have also led me to believe—though accurate measurements have not yet been made—that from these also, though the character of the secondary radiation in some cases differs enormously from that of the primary, the

energy of secondary radiation is proportional simply to the quantity of matter passed through by a primary beam of given intensity. Using sheets of different metals, equal weights are productive of a greater secondary ionization the greater the absorbability of this radiation by sheets of aluminium; so that on the assumption that the ionizing-power varies for these radiations at a rate of 5 or 6 times the absorbability in aluminium—evidence for which I have previously given—the energy of radiation from equal masses is approximately the same in each case. As an example, the radiation from tin was approximately 5 times as absorbable by aluminium as the primary radiation, while the ionization produced in the secondary electroscope by this radiation was about 29 times the ionization produced by the secondary radiation proceeding from an equal mass of air.

For the few metals experimented upon, the energy of secondary radiation is of the order of magnitude which would bring it into agreement with the law found for gases and light solids. Further experiments are being made to test this more accurately.

It should be observed that in these measurements the radiation from metals which is absorbed by a few millimetres of air under normal conditions has not been taken account of. This may or may not form a part of the radiation accounted for by the acceleration of the negative corpuscles or electrons in the intense electric fields in the primary Röntgen pulses. Further experiments on the subject are necessary.

The results of these experiments may be summarized thus:—

(1) The character of secondary X-radiation from gases differs slightly from that of the primary producing it. (From air the secondary has greater ionizing power in air.)

(2) The penetrating rays are transformed to a greater extent than the more absorbable rays. (See previous note.)

(3) The energy of secondary radiation from a given gas through which a primary beam of given intensity is passing is independent of the character of the primary radiation.

(4) The energy of secondary radiation from gases and those light solids which are the source of a radiation differing little in character from the primary, is proportional to the quantity of matter through which the primary beam of given intensity passes.

(5) In the passage of X-radiation through air at 0° C. and 76 cms. of the pressure, the diminution of intensity due to secondary radiation is of the order of magnitude .02 per cent. per centimetre.

N.B. This is a large fraction of the total loss of intensity due to all causes for fairly penetrating rays.

(6) Applying experimental results to the expression given by J. J. Thomson for the loss of energy per centimetre (due to radiation) in passing through a medium containing ions, and taking the negative corpuscles with $\frac{e}{m} = 7 \times 10^6$ and $e = 10^{-20}$ as the sources of the radiation, the number of these corpuscles or electrons per c.c. for air under normal conditions is of the order 10^{22} .

(7) *Quantitative* results show that the secondary radiation from metals, though of different penetrative power, is of the same nature as the primary X-radiation.

(8) Results of the order of magnitude of those given above have been obtained with all metals experimented upon, though the secondary radiation from them differs considerably in character from the primary.

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LXII. *The Thomson Effect in Alloys of Bismuth and Tin.*
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I. Introductory.

EXPERIMENTS on some of the electrical properties of Bismuth-Tin alloys have already been made by Rollmann †, von Ettingshausen and Nernst ‡, Hutchins §, Spadavecchia ||, and Schulze ¶.

The very interesting nature of the results obtained seemed to warrant a further study of the electrical behaviour of these alloys.

The present communication contains an account of some experiments on the Thomson effect, or the amount of heat evolved or absorbed by a current in passing along a conductor in which a temperature-gradient is maintained, in such alloys.

As is well known, this effect was first observed by Lord Kelvin **, who found that heat was evolved by a current passing down a temperature gradient in copper, whilst in iron an absorption of heat took place under similar circumstances.

* Communicated by Prof. J. J. Thomson.

† Rollmann, Pogg. *Ann.* lxxxiii. p. 78 (1851).

‡ Von Ettingshausen & Nernst, Wied. *Ann.* xxxiii. p. 477 (1888).

§ Hutchins, Amer. Jour. of Sci. xlviii. p. 226 (1894).

|| Spadavecchia, *Nuov. Cim.* ix. p. 432 (1899).

¶ Schulze, *Ann. der Phys.* ix. p. 555 (1902).

** W. Thomson, Phil. Trans. cxlvi. p. 649 (1856).