

5. For all substances, the potential-difference increases with pressure (except for very low pressures), with the E.M.F. producing the discharge, and the distance between the electrodes.

6. In air, and probably in all gases, the angular velocity of rotation is proportional to the E.M.F. producing the discharge, and increases as the spark-length decreases.

$$7. \text{ Since } \frac{\omega}{m} \propto \frac{K_1 K_2 S}{\int r^2 ds},$$

$$\frac{1}{T} \propto K_1 K_2 S ;$$

but since  $S$  increases with density and  $T$  also increases with density,  $K_1 K_2$  rapidly decreases as density increases.

8.  $K_1 K_2$  is independent of the distance between the electrodes (except in so far as the potential-difference in the discharge depends on it) but varies with the E.M.F. of the discharge.

I have to thank Professor J. J. Thomson for permission to work at the Cavendish Laboratory and for many valuable suggestions.

XLVIII. *Homogeneous Secondary Röntgen Radiations.* By CHARLES G. BARKLA, M.A., D.Sc., Lecturer in Advanced Electricity, and CHARLES A. SADLER, M.Sc., Demonstrator in Physics, University of Liverpool\*.

**THOUGH** there are many phenomena of Secondary Röntgen Rays still awaiting investigation, it seems desirable in publishing the results of recent experiments—principally on the homogeneous secondary radiations—that a general survey should be made of the whole subject of “Secondary X-Rays emitted by substances subject to X-Rays,” and that a more concise statement of the experimental results and the conclusions based on these should be given. This, indeed, appears a necessity not only in order to make intelligible the results of what would otherwise appear isolated experiments of little significance, but to exhibit the observed limitations or the generality of laws

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which are continually being tested by further experiments on a variety of substances and under a variety of conditions.

As has been shown in previous papers \*, the behaviour of substances subject to X-rays varies enormously with the atomic weight of the substance exposed, and generalizations cannot safely be arrived at except after an extensive series of experiments on a large number of elements.

The results which have so far been found to be perfectly general will be briefly stated †:—

All substances subject to X-rays are a source of secondary X-rays.

The radiation from a given element is independent of the physical state of the substance and of its mixture or even chemical combination with other elements.

The character of the secondary radiation from an element is independent of the intensity of the primary radiation producing it.

The intensity of secondary radiation from an element is proportional to the intensity of the primary radiation of definite character producing it.

The absorption by a thin sheet of any substance of the secondary rays from various elements subject to the same primary beam is a periodic function of the atomic weight of the radiating substance.

There are, however, groups of elements of neighbouring atomic weight into which substances may conveniently be divided; for when a primary beam of ordinary penetrating power is used, the radiations from the various elements in one group are very similar in properties, while those from elements in different groups differ considerably. But it should be understood that this grouping is somewhat

\* As frequent references are made to the following papers, they are denoted by the letters *a-g*:—

BARKLA: *a.* Phil. Mag. June 1903, pp. 685-698.

*b.* Phil. Mag. May 1904, pp. 543-560.

*c.* Phil. Trans. A, vol. 204, 1905, pp. 467-479.

*d.* Roy. Soc. Proc. A, vol. 77, 1906, pp. 247-255.

*e.* Phil. Mag. June 1906, pp. 812-828.

*g.* Phil. Mag. Feb. 1908, pp. 288-296.

BARKLA & SADLER: *f.* Phil. Mag. Sept. 1907, pp. 408-422.

† These results were given in the papers to which reference has already been made; later experiments have not revealed any exceptions. It appears quite possible, however, that under certain conditions exceptions will be found. Crowther, who by careful experiment has further verified some of these results (Phil. Mag. Nov. 1907), finds much less intense radiation from nickel when in combination as nickel carbonyl than we have obtained from the pure element in the solid state. As this cannot be accounted for by variation in the primary beams used, it is perhaps worthy of further investigation.

arbitrary, as elements of intermediate atomic weight emit radiations possessing intermediate properties, and the classification depends to a certain extent on the character of the primary radiation. It is, however, convenient for the purpose of description.

### H-S GROUP.

The group of substances of atomic weights from that of hydrogen to that of sulphur appears simplest in behaviour under X-rays of ordinary penetrating power.

Each element, when subject to such a primary beam, emits a secondary radiation which has almost exactly the same penetrating power as the primary producing it. The secondary beam is complex like the primary, and contains the rays of various penetrating powers in approximately the same proportion as the primary (*a* & *b*).

Though it is very difficult, if not impossible, to detect by direct methods a difference in the penetrating powers of primary and secondary beams, when the primary is not more than moderately penetrating, it appears from indirect evidence that the secondary radiation is always slightly more absorbable than the primary (*b*). With more penetrating primary rays the difference is more marked (*b* & \*).

The intensity of radiation emitted by these elements is proportional merely to the quantity of matter passed through by a primary beam of definite intensity, if of low to moderate penetrating power: in other words, the intensity of radiation from an atom is proportional to the atomic weight † (*a* & *b*).

The secondary radiation proceeding from one of these substances in a direction perpendicular to that of propagation of the primary is fairly completely polarized, when the rays are of the absorbable type (*d*).

The intensity of secondary radiation from each of these substances varies in different directions perpendicular to that of propagation of a polarized primary beam (*e*).

The amount of polarization in a primary beam, as indicated by the secondary rays, diminishes with an increase in the "hardness" of a given X-ray tube emitting the primary radiation.

\* Beatty, *Phil. Mag.* Nov. 1907, pp. 604-614.

† It was considered possible that the discrepancy in the case of hydrogen, as found by one of us, might be explained by the mixture of a small quantity of air. Crowther, however, from more recent experiments has concluded that hydrogen and helium in this group are exceptions to this law of intensity.

The secondary radiation from these substances is approximately twice as intense in the direction opposite to that of propagation of the primary rays as the average in directions at right angles, when the primary beam consists of rays of the easily absorbed type (*g*). (Polarization produces variation in different directions at right angles to the primary beam.)

This ratio varies somewhat with a variation in the character of the primary rays, but has not been found to exceed 2:1.

The results of all the experiments when an easily absorbed primary was used as the exciting beam, may be explained on the theory as given by Professor J. J. Thomson \* shortly after the earliest systematic experiments on light gases. The electric displacement in the primary Röntgen pulses when passing over the electrons produces accelerations in these in the direction of that displacement, and thus causes the emission of secondary pulses of equal thickness. The natural deductions from this theory have all been strikingly verified by experiments on substances of low atomic weight when subject to an easily absorbed primary beam.

Before the phenomena of secondary X-rays from these light atoms may be said to be fully understood, we must explain the effects produced when the primary rays change to those of more penetrating type. In experiments that have been described the secondary rays began to differ in penetrating power from the primary,—they were more easily absorbed; they gave less evidence of polarization of the primary beam, the variation falling from about 20 per cent. to 6 or 7 per cent. in experiments made while the primary became more penetrating; the ratio of intensity of secondary radiation in the direction opposite to that of propagation of the primary beam to that in one at right angles dropped considerably; the ratio of ionization in the secondary electroscope to that in one testing the primary beam increased slightly.

These results might be explained qualitatively either by the introduction of a secondary radiation of different type superposed on the almost perfectly scattered, or by the scattering becoming more imperfect by the introduction of forces of considerable magnitude other than those produced directly by the primary pulses during the passage of those primary pulses over the electrons, or by the intro-

\* 'Conduction of Electricity through Gases' (2nd edition) p. 321.

duction of a greater proportion of tertiary rays due to the emergence of the secondary rays from greater depths of the radiating substance, or by a combination of these.

Though the experiments, the results of which are stated above, were not performed concurrently, it was evident that the variation in intensity of secondary radiation exhibiting the polarity of the primary beam changed from about 20 per cent. to only about 6 or 7 per cent. as the X-ray tube became "harder," even before a difference between the penetrating powers of primary and secondary beams could be detected by direct comparison. It was not evident whether this change was actually one in the polarization of the primary beam itself or in the efficiency of the secondary rays in exhibiting a polarization of constant magnitude. The latter appeared the more probable when considered in conjunction with the changes that had been found in the ratio of intensities of secondary rays in a direction almost opposite to that of primary propagation and one at right angles. Further experiments were therefore made to determine if the changes were all attributable to the same cause. It was found, however, that although increasing the hardness of a given X-ray tube produced a decrease in the amount of polarization detected, the more penetrating portion of a primary which was transmitted through a sheet of aluminium did not exhibit less polarity but slightly more, indicating that the effect was due not merely to change in the penetrating power of the radiation but to some change in the polarity of the primary beam itself. This was supported by the fact that the secondary radiation did not become appreciably different in penetrating power from the primary producing it,—indicating a fairly perfect scattering. Finally, later experiments have shown that for a primary radiation proceeding from a tube in the state of hardness which has invariably been found to exhibit a minimum of polarity in the primary, the ratio of intensities of secondary rays in the two directions indicated has been such as would be given by an almost perfectly scattered radiation.

We cannot then attribute the decrease in the amount of polarization of a primary beam exhibited by the secondary rays to the scattered rays being only partially a scattered radiation or to imperfection of scattering, but it is almost certainly a decrease in the polarity actually existing in a primary beam when the tube becomes harder.

These results are possibly due to the more swiftly moving cathode particles in the X-ray tube being productive of more secondary cathode rays in the anti-cathode. As the

secondary cathode particles are not directed like the primary cathode rays, they produce radiation which is not polarized. The greater the number of secondary cathode particles produced, the less is the polarity of the complex radiation. As the X-radiation from the secondary cathode particles is probably less penetrating than that due to the primary cathode particles, the more penetrating portion of the complex X-radiation exhibits slightly more polarity than the more easily absorbed.

The small increase observed in the intensity of secondary radiation from air, paper, &c., as measured by the ionization produced in an electroscope, when the primary beam is made more penetrating, is possibly due to the superposition of a homogeneous unscattered radiation, such as is emitted by elements of higher atomic weight. This would account for the complex secondary radiation differing more and more in penetrating power from the primary as the latter became more penetrating; for it has a definite penetrating power characteristic merely of the element emitting it. Though experiments have not yet been made to analyse this secondary radiation set up by the more penetrating radiation, it appears, for reasons discussed later, exceedingly probable that such a radiation does appear when a penetrating primary beam is used.

A point still awaiting investigation is the change in the observed ratio of intensities of secondary radiation in directions approximately opposite and perpendicular to that of primary propagation. Experiments have been made to ascertain the amount by which this ratio is affected by a change in the polarization of the primary beam, by the superposition of tertiary rays in greater proportion, and by the superposition of homogeneous radiation characteristic of the radiating element. In these later experiments, however, the deviation from the theoretical ratio for perfect scattering has through all the changes made in the primary beam been much less than in the first experiments; and it has been found that even a fairly penetrating primary beam—much more penetrating than any used in the experiments referred to in a previous paper (*a*)—sets up secondary rays whose intensity distribution is within a few per cent. of that which would be given by perfect scattering. This matter is being further investigated\*.

\* It ought to be remarked, that though an elementary consideration of the production of secondary rays indicates that the intensity of radiation is the same in the forward and backward directions, and that each of these is double that in a direction at right angles, a more complete

## Cr-Zn GROUP.

The radiation proceeding from elements of atomic weight between those of chromium and zinc, when subject to X-rays of ordinary penetrating power, is of a very different type from that discussed, for from no two elements in this group is the penetrating power the same. The absorption by a thin sheet of aluminium  $\cdot 0104$  cm. thick is, between these limits of atomic weight, a decreasing function of the atomic weight, varying from 94 per cent. for the radiation from chromium to 64 per cent. for the radiation from zinc. [One of the primary beams used was absorbed to the extent of about 34 per cent.]

*Homogeneity.*—One of the most remarkable features about the radiation from any one of these elements is that though the primary rays incident upon the substance are very heterogeneous, that is consist of rays varying considerably in penetrating power, the secondary rays are homogeneous. This point has been briefly referred to in a previous paper (*f*).

To give a particular example:—The ionization produced in a given electroscope by a primary X-ray beam was diminished by 51 per cent. by placing a sheet of aluminium  $\cdot 0208$  cm. in thickness in its path; after 77 per cent. had been absorbed by aluminium, a similar plate produced a further diminution of this ionization by 27 per cent.; after 91 per cent. had been absorbed the same plate cut off only 18 per cent., showing that the rays after each transmission became on the average more and more penetrating. This effect has been explained as due to the more absorbable constituents being sifted out.

Although such a primary beam produced in one of this class of substances the secondary radiation experimented upon, it was found that the secondary radiation was of an entirely different type, being equally absorbed after transmission through sheet after sheet of absorbing substance.

The radiation from thick copper was found not to differ appreciably from that from a very thin sheet which was only thick enough to absorb 14 per cent. of the primary rays. Thus the radiations from the deeper layers after transmission

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theory shows that these results can at best be only approximately true. It is only necessary to consider the action of the magnetic field in the primary pulses on the electrons as they begin to move under the action of purely electric forces, to see that dissymmetry must exist. A complete theory must also take into consideration the distribution of the tubes of electric force round each radiating electron.

through the surface layers were of the same character as those from the surface layers. Consequently, in dealing with these secondary rays it is not necessary as in the H—S group to deal with very thin plates in order to determine the character of the radiation as emitted by the atoms themselves.

Using zinc as the radiating substance, the direct ionizing effect of the secondary rays was determined, and afterward the ionization produced by the same beam after transmission through thin sheets of zinc and aluminium placed at a distance of several centimetres from the detecting electro-scope in order to avoid complications due to the more easily absorbed corpuscular secondary rays from the metal sheet.

The effect of the radiation from air was determined by separate experiments, and correction was then made for this in each observation, though when a large proportion of the secondary rays was absorbed, the air radiation was quite a considerable fraction of the whole and the possible error was as a consequence greatly increased.

Below are tabulated the percentage absorptions by a plate of zinc .00131 cm. thick and one of aluminium .0104 cm. thick of the secondary beam direct from zinc and of this beam after transmission through various thicknesses of aluminium. These results exhibit the striking homogeneity of the radiation from zinc.

TABLE I.  
Radiation from Zinc (thick sheet).

I. Percentage Absorption by Al previous to absorption in column II. or III.	II. Percentage Absorption by Zn (.00131 cm.) after absorption in column I.	III. Percentage Absorption by Al (.0104 cm.) after absorption in column I.
0	36.5	67.5
22	36.2	67
67	35.4	—
0	35.8	—
89	35.4	67
97	33.9	66
0	34.2	—

Similar experiments were made on the absorption of the radiation from zinc by zinc when that radiation had been



passed through various thicknesses of zinc to absorb different proportions of it.

The radiation from copper was examined in the same way.

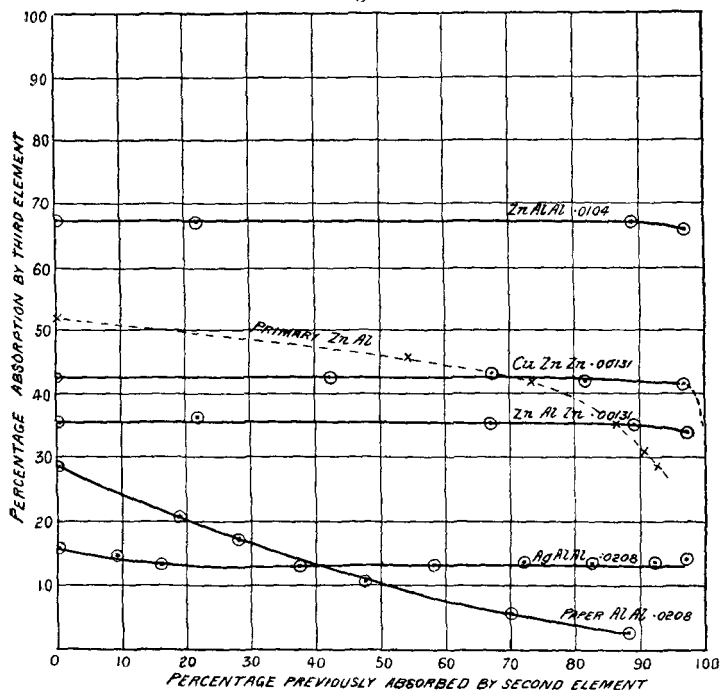
TABLE II.  
Radiation from Copper (thick sheet).

I. Percentage Absorption by Zn previous to absorption in column II.	II. Percentage Absorption by Zn (.00131 cm.) after absorption in column I.
0	43
44	44
0	41.4
42.6	42.6
67.5	43.1
81.5	42
96.7	41.8
0	42.5

All these experiments show extremely little change in the percentage absorption even after almost complete absorption. The contrast between primary and secondary beams is strikingly shown in fig. 1 (p. 559), in which the absorptions are represented by ordinates and the amount previously absorbed by abscissæ. The corresponding curve for the secondary radiation from paper (in this case subject to penetrating primary rays) is given for comparison (fig. 1).

*Independence of Primary Rays.*—To exhibit the independence of the penetrating power of the secondary radiation from one of these metals Cu, of that of the primary producing it, we have tabulated below the absorbability of various primary rays and that of the secondary rays produced by these. Though the absorption of the primary by aluminium .0208 cm. thick varied from 52 to 18 per cent., the absorptions of the corresponding secondary beams from copper by aluminium .0104 cm. thick were as nearly as observable the same, the experimentally determined values being 58.3 and 58.1 per cent. respectively. This constancy in character makes accurate experiments on these radiations possible.

Fig. 1.



Note.—Cu Zn Zn .00131 indicates :—Copper radiation after transmission through Zn is absorbed by Zn .00131 cm. thick to extent shown by ordinates.

TABLE III.  
Radiation from Copper (thick sheet).

I. Percentage Absorption by Al of Primary Radiation previous to incidence on Cu radiator.	II. Percentage Absorption of Primary Rays by Al (.0208 cm.) after absorption given in column I.	III. Percentage Absorption of Secondary Rays by Al (.0104 cm.).
0	..	58
52	..	58.6
0	52	58.3
77	27	58.8
0	51	58.4
91	18	58.1
0	51	58.8

Each of these elements therefore emits a characteristic radiation which is independent of the penetrating power of the primary beam setting up this radiation, and being homogeneous, the absorption-coefficient calculated from the relation  $I = I_0 e^{-\lambda x}$  has a value which is independent of the thickness  $x$  of absorbing substance\*—a property which appears to be unknown among X-ray beams hitherto experimented upon.

The absorption-coefficients for the radiations from Fe, Co, Ni, Cu, and Zn, when absorbed by Al, Fe, Cu, Zn, Ag, Sn, and Pt have been given in a previous paper (*f*).

Though it has been shown that the secondary radiation from some of the substances in this group (Cr-Zn) is remarkably homogeneous in comparison with the primary which produces it, the test applied is not one of extreme delicacy, and the presence of the scattered radiation similar to that of the first group (H-S) and of intensity given by the law found for that group would be exceedingly difficult to detect, as it would produce only about  $\frac{1}{300}$  of the total ionization actually produced by the secondary rays from a very thin sheet of copper. Now we have seen that a radiation after transmission through metals may contain a considerable proportion of the radiation which is characteristic of the metal traversed and which was not in the incident radiation. This acquired radiation may even, if the substance traversed has almost completely absorbed the incident radiation, constitute the bulk of the transmitted radiation. In such a case, experiments on the transmitted beam in order to analyse its constituents would be misleading, the constituents not being present in the original beam.

To eliminate the possibility of this error, we have tested the radiation from copper after transmission through thin sheets of copper by absorbing by further plates of copper. Thus radiation of a fresh type was not introduced.

It was found that after absorbing 98.3 per cent. of the copper radiation by copper, the absorption by copper .00296 cm. thick had dropped from 74 to 70 per cent. The effect was more pronounced in the case of the radiation from iron, the numerical data for which are given below.

\* After transmission through sheets of absorbing substance, secondary rays are superposed on the transmitted radiation, and the resultant radiation in some cases ceases to be even approximately homogeneous. This effect can, however, be readily distinguished from true heterogeneity by using as absorbers only those substances in which a radiation of different type is not stimulated.

TABLE IV.

## Radiation from Copper (thick sheet).

I. Percentage Absorption by Cu previous to absorption by Cu, Zn, or Al.	II. Percentage Absorption by Cu, Zn, and Al after absorption in column I.		
	Cu .00293 cm.	Zn .00262 cm.	Al .0104 cm.
0	74	69.7	72
98.3	70	66	68

## Radiation from Iron (thick sheet).

I. Percentage Absorption by Fe previous to absorption by Fe, Cu, or Al.	II. Percentage Absorption by Fe, Cu, and Al after absorption in column I.		
	Fe .00313 cm.	Cu .00296 cm.	Al .0104 cm.
0	80.5	91.5	90
80	79.8	91	89.5
96	76.9	86	83.5

There was thus evidence of a slight heterogeneity even in these radiations.

*Scattered Rays.*—To test if this heterogeneity could be accounted for by the mixture of a scattered radiation, like that from light atoms, with the homogeneous radiation, a direct comparison was made between the ionization produced by the secondary beams from thin sheets of copper [.00067 cm.] and paper, subject to the same primary radiation. The paper which was used had ten times the mass of the thin copper, yet the ionization produced by the secondary rays from the copper was 19.5 times that produced by the secondary rays from paper even though a greater proportion of the radiation from copper was absorbed by the copper itself than that from the paper in the paper. As sheet after sheet of aluminium was placed in the path of the two secondary beams, the copper radiation was absorbed to a much greater extent than the radiation from paper; thus 34 per cent. of the radiation from paper was transmitted

through aluminium  $\cdot 0416$  cm. in thickness, while only  $\cdot 7$  per cent. of the copper radiation got through. The ratio of the ionization due to the copper radiation to that due to the rays scattered from paper, after transmission through  $\cdot 0416$  cm. Al had dropped to  $\cdot 401:1$ . After transmission through  $\cdot 0782$  cm. of Al the two radiations appeared approximately equal in penetrating power, the last  $\cdot 26$  per cent. of the copper radiation being much more penetrating than the homogeneous radiation which had been practically all absorbed. When the two transmitted radiations were approximately of the same character, the ratio of their ionizing effects was about  $\cdot 18:1$ ; or from equal masses of copper and paper—disregarding all internal absorptions the intensities of the penetrating rays were in the ratio  $1\cdot 8:1$ .

TABLE V.

I. Thickness of Al in path of Secondary beams.	II. Percentage of Cu radiation absorbed.	III. Percentage of Paper radiation absorbed.	IV. Ratio of ionizations due to Secondary beams from equal masses of Cu and Paper.
0	0	0	195.5 : 1
$\cdot 0208$	94.5	51.8	22.1 : 1
$\cdot 0416$	99.3	66	4.01 : 1
$\cdot 0574$	99.6	71	1.94 : 1
$\cdot 0782$	99.74	78	1.88 : 1
$\cdot 0990$	99.8	83	1.83 : 1

Allowing for the small extra absorption of the penetrating portion of the copper radiation in the copper plate itself above that of the corresponding rays in the paper—quantities which were determined by separate experiments—the radiation from copper must have contained approximately twice as much of the penetrating radiation as the radiation from paper.

By using a thicker copper plate as radiator the intensity of secondary radiation was increased, but the correction for absorption in the metal itself was also increased so that the result could not be regarded as more accurate, this correction not being obtainable with great accuracy. The conclusion was however practically identical with the above. We thus see that mixed with the homogeneous radiation from copper

is a more penetrating radiation. The most penetrating portion of this is about twice as intense as the corresponding radiation from substances of the H-S group.

The radiations from other elements of the Cr-Zn group have not been examined so minutely as that from copper, but it has been seen that these also contain a small quantity of a more penetrating radiation which is probably scattered radiation. This more penetrating radiation was more evident in the radiation from thick iron, probably because the homogeneous iron radiation being very absorbable emerges from a thinner surface layer, while a scattered radiation emerges from greater depths than in the metals of higher atomic weight owing to the greater transparency of iron than substances of higher atomic weight. Consequently the scattered rays—if we may assume them to be such—are in reality from a much greater mass of iron than the homogeneous rays, and produce more than their appropriate portion of the total ionization.

It may be objected that in this case the radiation was transmitted through a second substance Al, and may have contained a considerable quantity of secondary radiation from Al of a kind not existent in the original radiation from copper. The production of a secondary radiation more penetrating than the primary producing it is, however, contrary to all experience.

*Energy.*—The ionization produced by the secondary rays from one of the elements of this group has been shown to be enormous in comparison with that produced by the secondary scattered rays from an equal mass of an element of low atomic weight. From a sheet of copper .00067 cm. thick, absorbing 14 per cent. of the primary radiation, the secondary radiation produced an ionization in the detecting electro-scope 200 times as great as that from an equal mass of paper. Correcting for absorption of primary and secondary rays, the ratio of ionization produced by the rays from equal masses of copper and paper was approximately 300:1. This is considerably greater than would have been found if all the radiation absorbed had been simply scattered as an untransformed radiation. This, however, by no means gives us a measure of the energy of the secondary rays, for these are of much more absorbable type than the primary. The percentage absorption by a thin sheet of aluminium is about five times as great for these secondary rays as for the primary. If we assumed the same ratio for the ionizations produced in air by the two radiations if of equal intensity, we should be led to conclude that the energy of this homogeneous

radiation is about 45 times that of the scattered radiation from an equal mass of paper, and about  $\frac{1}{3}$  the total energy absorbed in the copper\*.

Though it is impossible by such experiments to determine the energy with accuracy, we may safely conclude that the energy of the homogeneous radiation is many times greater than the energy of secondary radiation scattered from an equal mass of one of the light elements.

Comparisons of the ionizations produced by the rays from other elements of this group have been made. They are all of the same order of magnitude.

*Distribution.*—It has been shown by one of us that the secondary radiation from thick copper, when this is subject to a primary beam of ordinary penetrating power, is approximately equally intense in a direction almost opposite to that of propagation of the primary and in a direction at right angles. As probably 98 per cent. of the ionization produced by the secondary radiation from thick copper is due to the homogeneous rays, this may be said to be the result for the homogeneous rays alone.

From thick iron, however, the radiation varied in intensity by an amount represented by the ratio 1.1 : 1 in these two directions. But as we have shown, the heterogeneity of the radiation from thick sheets of iron is more marked, and this can be accounted for by the fact that from iron the homogeneous rays are very easily absorbed, consequently scattered rays emerge from a much thicker layer and appear in more than their normal proportion. The ratio 1.1 : 1 verifies this by showing the presence of a radiation which is controlled by the electric field in the primary pulses.

The result is of the order of magnitude that would be given by a mixture of scattered rays of about the same intensity as found in the radiation from copper with the characteristic radiation uniformly distributed.

*Polarization Experiments.*—Though very careful experiments have been made with iron, copper, and zinc as secondary radiators placed in a partially polarized primary beam of Röntgen radiation, the secondary rays from these have not been found to give evidence of any polarity. Thus the intensity of secondary radiation in a given direction is independent of the position of the plane of polarization of the primary beam producing the radiation; in other words,

\* The homogeneous radiation has been assumed to be distributed uniformly in all directions and the scattered radiation to be proportional to  $\sin^2 \theta$ , where  $\theta$  is the angle between the direction of radiation considered and that of acceleration of the radiating electron.

the intensity of secondary radiation from members of this group is independent of the direction of electric force in the primary radiation. Again, this result may be taken as applicable to the homogeneous rays, as these constitute the bulk of the radiation from these metals.

*Efficiency of Primary Rays as Secondary Ray Producers.*—Although in addition to the relatively small amount of scattered radiation, rays of only one penetrating power were emitted by an elementary substance upon which a heterogeneous primary beam fell, it was still possible that only one constituent (rays of one penetrating power) in each heterogeneous primary beam was producing this radiation. It was therefore important to determine to what extent each constituent of the primary beam was effective in producing these secondary rays.

To do this, a portion of the primary beam direct from the X-ray tube was sent through one electroscope while another portion was incident on a secondary radiator, some of the rays from which passed through a second electroscope. The method was then simply to place absorbing plates in the primary beam before falling on the radiator, and to observe the extent by which the primary and the secondary radiations were reduced. It is obvious that the more penetrating constituents of the primary beam penetrate to greater depths than the absorbable constituents, and so are really transmitted through a greater mass than these. Hence, if two homogeneous constituents of primary radiation in passing through equal masses of radiating substance were equally efficient as secondary-ray producers, the radiation emitted by a thick plate would be produced principally by the more penetrating constituents; consequently an absorbing plate placed in the position indicated, would, by cutting off the more easily absorbed constituents, produce less diminution of the ionization in electroscope  $E_2$  than of that in  $E_1$ . It was therefore necessary to use as the radiator a sheet of metal which would absorb very little of the primary radiation, so that even the deepest layers would transmit different constituents in proportions approximately the same as those transmitted through the first surface-layer.

It was found that a sheet of Cu  $\cdot 00067$  cm. in thickness when placed in the primary beam produced an absorption of only 14.5 per cent., as measured by the ionization produced in an electroscope. This was considered sufficiently thin for use as a radiator. The deflexions of the electroscopes were first observed when no absorbing plate was used. Aluminium



plates of thickness shown in column I of Table VI. were placed in the primary beam, and the deflexions of the primary and secondary electroscopes were diminished by the amount given in columns III and IV.

TABLE VI.

Radiation from Copper (thin sheet absorbing 14.5 per cent. of primary rays.)

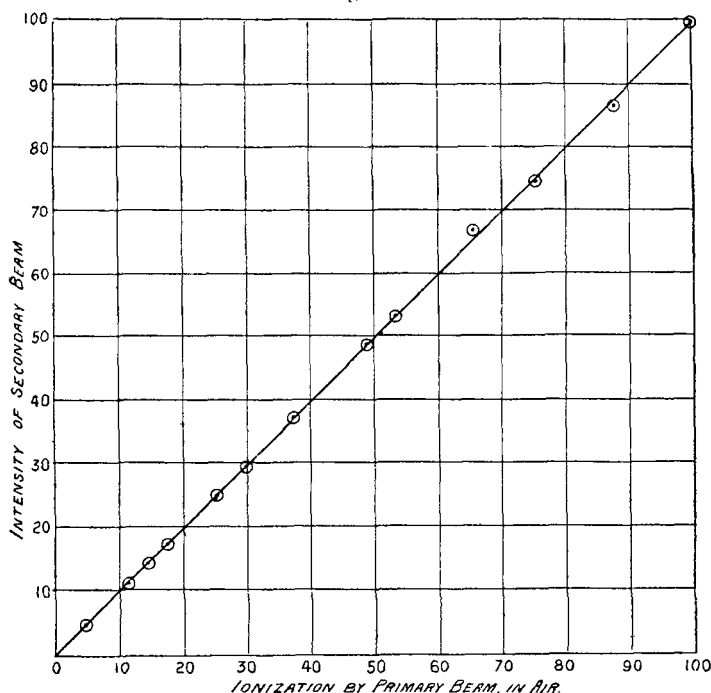
I. Thickness of Al in Primary beam in centimetres.	II. Absorption of Primary by Cu (.00293 cm.) after passing through Al in column I.	III. Percentage of Primary absorbed by Al in column I.	IV. Percentage diminution of Secondary by Al in column I. absorbing Primary.	V. Ratio of Ionizations in Secondary and Primary electroscopes (relative).
0	84	0	0	1
.0032	82.8	12.2	13.6	.98
.0064	81.4	24.9	25.5	.99
.0104	80.3	34.2	33.1	1.01
.0168	77.5	46.7	46.6	1.00
.0208	75.9	51.1	51.4	.99
.0312	72.3	62.9	62.9	1.00
.0416	69.6	70.2	70.5	.99
.0520	65.2	74.6	75.0	.98
.0728	60.4	82.4	82.3	1.00
.0936	57.0	85.8	85.8	1.00
.124	51.2	88.6	88.9	.97
.248	41.7	95.4	95.3	1.02

In fig. 2 the ionization produced by the primary beam in air is indicated by abscissæ and that produced by the corresponding secondary beam from a thin sheet of copper as ordinates, when different portions of the primary beam have been absorbed.

As the secondary beam is practically homogeneous we have exhibited the relation between the ionization produced by a primary beam in the air, and its power of producing secondary rays in copper. We are thus led to the conclusion that the intensity of this homogeneous secondary radiation set up in a thin sheet of copper is proportional to the number of ions the primary beam would produce in a thin layer of air. Thus if two beams of Röntgen rays, which in passing through

a thin film of air would produce equal ionizations in that air, be sent through a thin sheet of copper, the intensity of

Fig. 2.



secondary radiation produced on that sheet by one beam will equal that produced by the other, even though one is three or four times as penetrating to copper as the other one. As for such ranges of penetrating power as are possessed by the constituents of such a primary beam, the relative ionizations produced by those constituents in different substances are usually fairly constant, it is highly probable that the intensity of the homogeneous rays from copper is through wide ranges of penetrating power of the primary proportional to the ionization which takes place in the copper, and is independent of the character of the primary producing it.

It does not necessarily follow from this that the process of ionization produces the radiation, but it seems to indicate that the energy of the homogeneous secondary radiation is, for such ranges in penetrating power, proportional to the energy of the primary beam spent in the process of ionization.

When the primary radiation was transmitted through

copper or iron before falling on the copper radiator, the ratio of intensity of secondary radiation to ionization produced by the primary beam dropped slightly, showing that the radiation transmitted through these substances was less efficient as a secondary-ray producer in comparison with its power of producing ionization in air. This may have been due to the fact that in transmission through these plates, a gradually increasing quantity of secondary radiation from the plates was superposed on the primary. This being in one case of the same penetrating power as the secondary emitted by the radiator, and in the other more easily absorbed than it, would not afterwards produce secondary rays in the copper (see later). When the radiation was absorbed by zinc, the ratio remained fairly constant. This result would, on the corresponding theory, be due to the fact that the radiation from zinc is slightly more penetrating than that from copper, consequently the zinc radiation acquired in the primary beam would be capable of stimulating a feeble secondary in copper. (See Table VII.)

TABLE VII.

Radiation from Copper (thin sheet absorbing  
14.5 per cent. of primary rays).

I. Thickness of plate in Primary beam.	II. Percentage of Primary absorbed by Zn in column I.	III. Percentage diminution of Secondary by Zn in column I absorbing Primary.	IV. Ratio of Ionizations in Secondary and Primary electroscopes.
Zn .00131 cm.	59.4	59.6	.99
.00262 "	77.5	77.6	.99
.00393 "	84.8	84.8	1.00
.00524 "	89.1	90.1	.91
.00786 "	93.5	93.6	.98
.01179 "	97.2	96.3	1.32
Cu .00067 cm.	43.5	45.1	.97
.00134 "	65.0	66.5	.95
.00296 "	82	84.8	.84
.00592 "	90	91.6	.84
.01184 "	97	98	.66
Fe .00315 cm.	77.2	80.8	.84
.00630 "	89.0	91.4	.78
.00945 "	93.0	95	.71

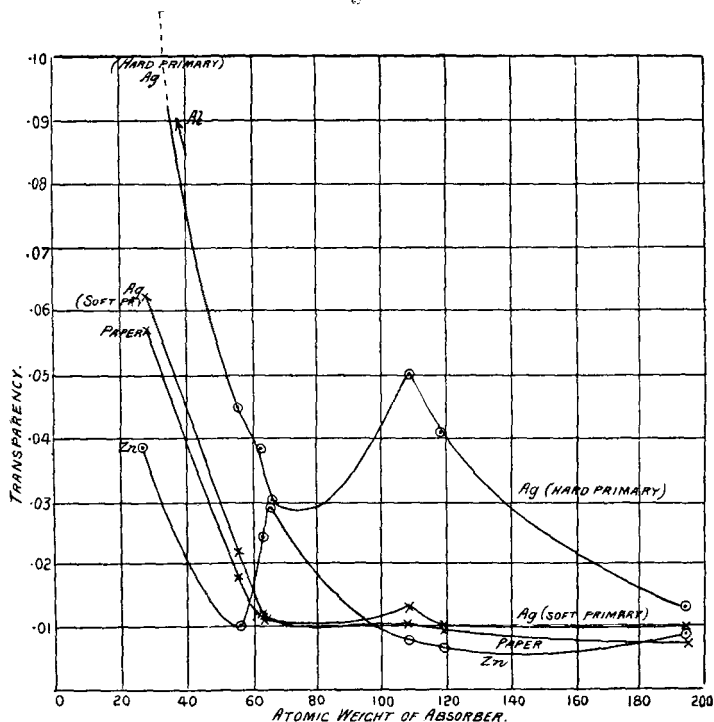
Whatever may be the true explanation, these results show that the proportionality exhibited after absorption by aluminium is not general even when copper is the radiating substance. This result may be contrasted with the corresponding phenomena exhibited by the homogeneous radiation from silver. In these experiments the homogeneous rays disappeared when the primary beam was made more absorbable and more efficient as an ionizer of air. The difference is almost certainly due to the fact that in the latter case the primary radiation passes from one more penetrating to one more easily absorbed than the secondary radiation characteristic of the element exposed to the primary rays. It seems highly probable therefore, that with sufficiently absorbable primary rays no such relation as that shown by fig. 2 would be obtained, but that the secondary would disappear while the primary still produced considerable ionization in air. It will be interesting to learn if a primary which ceases to stimulate the homogeneous radiation ceases also to produce ionization in the radiating substance. We, of course, know that elements of the H-S group are ionized, but do not emit a homogeneous radiation which can be detected. This appears to indicate no necessary connexion between ionization and radiation, but is not conclusive for various reasons.

*Special Penetrating Power.*—In studying the absorption of these homogeneous radiations by a number of elements, it was found that the relation between the absorption by a given substance of the various homogeneous radiations from elementary substances and the atomic weight of those radiating substances was similar for all absorbing substances, except in the case of the radiating and absorbing elements being identical or possessing neighbouring atomic weights. Each substance appeared to be especially transparent to its own radiation, and to a less extent to that from elements of neighbouring atomic weight.

The transparency of various elements to an ordinary heterogeneous beam of X-rays has been investigated by Benoist, who studied the phosphorescence produced by the beam after passing through absorbing substances. He compared the transparencies by finding the mass of a prism of absorbing substance of definite cross-section, which when placed in the path of the beam absorbed it by a definite amount. The relation between the transparency so defined and measured, and the atomic weight of the absorbing substance was shown by a curve similar to that for paper given in fig. 3. It shows a rapid decline of transparency, with increase in atomic weight for low atomic weights, the

rapidity of the fall of transparency diminishing with an increase of atomic weight. In the case of very soft rays this decline becomes a slight incline.

Fig. 3.



By using thin plates of absorbing elements and testing by the ionization method the percentage diminution of intensity of the secondary beams by transmission through these plates, it was easy to calculate the thickness and hence the mass per unit cross-section necessary to absorb a given proportion—in this case 75 per cent. Some of these results we have given in a previous paper (*f*)\*. They show that in place of the usual relation between transparency and atomic weight there is a strongly marked deviation in each case in the neighbourhood of the atomic weight of the radiator, the rays from an element being especially penetrating to that element

\* In the paper referred to the numbers given in Table II. represent mass in grammes, not thickness in centimetres as stated.

and to a less extent to elements of neighbouring atomic weight.

That this special penetrating power is not due to the constituent easily absorbed by the radiating substance having been sifted out before emergence through the surface layer might be inferred from the fact of its homogeneous character, unless of all the constituents in the radiation as emitted from the atom itself this was the only one transmitted through even fairly thin layers of the substance. But we find other secondary rays transmitted with almost the same facility. We may conclude, therefore, that it is not merely from the surface of relatively thick sheets that the radiation emerges in a homogeneous state, but that it is so emitted by the atoms themselves. The special power of penetration is thus a specific property of the secondary rays and does not appear to be due to previous selective absorption.

*Tertiary Rays.*—Some of the most interesting phenomena in connexion with these homogeneous rays were those shown by experiments made in order to investigate the special penetrating power of these rays.

When the characteristic homogeneous radiation from iron was passed through a thin sheet of copper—a substance whose characteristic radiation is of more penetrating type—it was partially absorbed, and the transmitted radiation appeared unchanged in character.

When, however, the radiation from copper was passed through iron there was superposed on the copper radiation a considerable quantity of iron radiation; when the thickness of the absorbing plate of iron was sufficient to produce almost complete absorption, the bulk of the transmitted radiation was iron radiation.

Similar experiments were made on copper and zinc. The radiation from the former, which is more absorbable than that from the latter, when passed through zinc was transmitted without admixture of other radiations, but when the radiation from zinc was transmitted through copper it became more like the copper radiation. The effect was not so well marked as in the case of the transmission of copper radiation through iron.

Thus a characteristic homogeneous radiation was emitted by a metal when the primary beam to which the metal was exposed was of more penetrating type than the characteristic radiation. When the primary was of a more absorbable type, this characteristic secondary radiation was not emitted\*.

\* Details of these experiments will be given later.

## Ag-I GROUP.

When subject to primary beams of moderate penetrating power such as those used in these experiments, the elements of atomic weights from that of silver to that of iodine are exceedingly susceptible to small changes in the penetrating power of that primary radiation, both as regards the character and the intensity of the secondary rays that they emit. This is indeed the most remarkable feature of this group of elements.

Silver and tin are the only elements of this group which have been examined in any detail, but they appear from superficial observation to be typical of the whole group. In previous papers it has been shown that the radiation from these two when subject to a primary beam of only moderate penetrating power, is not a scattered radiation like that which proceeds from elements of the H-S group, for it differs much more in penetrating power from the primary producing it than the radiation from the elements of that group, though not so much as the radiation from Cr, Fe, Cu, &c. The radiation does not exhibit the polarity of a primary beam where such exists, and it is not distributed in the manner of the radiation from substances of low atomic weight, the intensity in a direction almost opposite to that of primary propagation being approximately equal to that in a direction at right angles. It was not possible, however, to perform this experiment with anything like the degree of accuracy with which it was done in the case of the radiation from Fe, Cu, &c., because the ionization produced by the secondary beams from Ag and Sn was much less intense.

*Secondary Scattered Rays.*—Experiments with the softest rays procurable from an X-ray tube of ordinary type, however, considerably simplified the secondary radiation, for it was found that the secondary rays from silver then differed very little in penetrating power from the soft primary. When the intensity of secondary radiation set up by a powerfully polarized primary was examined in the two principal directions at right angles, it was found that it varied by approximately the same amount as that from elements of the H-S group, thus exhibiting the same perfection of scattering. When tin was examined in the same way, the variation in intensity was found to be about half that exhibited by the rays from paper and from silver. Thus by using a very soft primary radiation, an almost purely scattered secondary radiation was emitted by silver, and a radiation consisting of a large proportion of scattered rays was emitted from Sn.

To compare the intensity of this scattered radiation from silver with that from elements in the H-S group, the ionization produced by the secondary radiation from a thin sheet of silver .00064 cm. thick was compared with that produced by the radiation from paper. The masses of silver and paper emitting the secondary rays were .2695 gr. and 2.72 gr. respectively. The relative ionizations produced by the secondary rays from these were 148 and 280. From other experiments on the absorption of the primary beam by sheets of silver and paper of different thicknesses, it was estimated that about 60 per cent. of the silver radiation and 75 per cent. of the paper radiation was transmitted through the surface layer. The intensities of radiation from these masses were, therefore, in the ratio 37 : 56 approximately. From equal masses this was 37 : 5.6, or 6.5 : 1 approximately.

As the primary radiation incident on silver became more penetrating, the ionization produced by the secondary rays increased enormously, the variation of intensity in the two principal directions at right angles to that of propagation of the primary rays gradually decreased from its original amount—about 14 per cent.—until it was inappreciable, though with the same primary the variation in the intensity of radiation from carbon had only dropped to about 6.5 per cent. The evidence of polarity of the primary given by the secondary rays from silver thus disappeared, while that given by the rays from carbon simply decreased from 14 per cent. to 6.5 per cent. It should, however, be noticed that the ionizing effect of the secondary rays from silver increased considerably, and when the evidence of polarity disappeared the total secondary ionization had increased about tenfold, so that such an effect would have been produced by the superposition of the homogeneous radiation, like that emitted by Cu, Fe, Zn, &c.; for such a radiation gives no evidence of polarity in a primary beam, being uniformly distributed around that beam\*.

\* An early experiment by one of us on the radiation from tin (*e*) indicated that the scattered radiation was not emitted in even the intensity that could be given by an element of the H-S group. The experiment was performed by comparing a very penetrating portion of the radiation from tin with that from paper. There are possibilities which make such an experiment inconclusive, and we feel that it requires verification. If the numerical values for the polarization given in Table VIII. could be taken as strictly accurate throughout, we should be led to conclude that the evidence of polarity disappeared more rapidly than could be accounted for by mere superposition of the homogeneous radiation, but the measurements in the final stages were too uncertain for such a conclusion to be based on them. We have, therefore, no conclusive evidence of a disappearance of the scattered radiation.



The evidence of polarity of the primary given by the radiation from tin disappears for even softer primary rays than in the case of silver. This must be connected with the fact that the characteristic homogeneous radiation from tin is less penetrating than that from silver, and is set up by a less penetrating primary radiation. It thus appears earlier in the process of hardening the primary and swamps the effect of the scattered radiation sooner.

TABLE VIII.

I. Absorption of Primary by .01 Al.	II. Ratio of Ionizations in Secondary and Primary electroscopes.		III. Percentage Variation of intensity of Secondary radiation exhibiting polarity of Primary beam.	
	C radiator.	Ag radiator.	C radiator.	Ag radiator.
35.5	.303	.180	14	11.5
22.6	.340	.359	10.95	4.45
32.3	.318	.305	12.9	6.2
32.0	.315	.369	12.9	4.5
30	.349	.821	9.9	2.8
29.4	.353	.844	9.6	2.45
28.6	.364	1.12	9.15	.9
28.9	.380	1.35	7.5	.75
27.3	.405	1.62	7	.45
25.6	.425	1.82	6.5	0

*Homogeneous Rays.*—An analysis of the radiation from silver similar to that made of the radiation from elements of the Cr-Zn group shows that when the primary radiation is moderately penetrating, such a homogeneous secondary radiation constitutes the bulk of the rays emitted. Absorption by thin sheets of aluminium showed slight heterogeneity at first, such as would be evident if the scattered radiation were superposed on the more penetrating homogeneous radiation. After the absorption of this more easily absorbed scattered radiation the remainder appeared perfectly homogeneous.

The contrast between the constitution of the copper and silver radiations is shown by the curves given in fig. 1. In the copper radiation the homogeneous rays are more easily absorbed than the scattered rays, so the curve is initially horizontal and finally slopes downwards. In the silver radiation the scattered rays are on the average more easily

absorbed than the homogeneous rays, consequently the curve dips initially and finally becomes horizontal. The absorptions at successive states are shown in the following tables. With these results may also be contrasted those obtained for the scattered radiation from paper.

TABLE IX.  
Radiation from Silver (thick).

Thickness of Al placed in Secondary beam from Ag.	Percentage diminution of Ionization produced by Secondary rays by trans- mission through Al in column 1.	Percentage diminution of Ionization by Second- ary rays due to absorp- tion by further sheet of Al (.0208 cm.).
0	0	15.9
.0104 cm.	9.2	14.8
.0208 "	16	13.8
.0574 "	37.7	13.1
.124 "	58	13.5
.182 "	72	14
.263 "	82.5	13.6
.387 "	92	13.8
.526 "	97	14.2
0	0	16

TABLE X.  
Radiation from Paper.

Thickness of Al placed in Secondary beam from Paper.	Percentage diminution of Ionization produced by Secondary rays by trans- mission through Al in column 1.	Percentage diminution of Ionization by Second- ary rays due to absorp- tion by further sheet of Al (.0208 cm.).
0	0	28.1
.0104 cm.	18.7	20.9
.0208 "	28	17.4
.0574 "	47.5	10.9
.182 "	70	5.8
.584 "	88	2.5
0	0	27.4

## W-Bi GROUP.

The radiations from the elements with atomic weights from that of tungsten to that of bismuth have not been examined minutely. They, however, appear to be very similar to the rays from Cu, Zn, &c. The ionization produced by these rays is of the order of magnitude of that produced by the rays from elements of the Cr-Zn group; but there appears slightly more variation in the character due to changes in the primary rays.

Though accurate observations have not been made, it appears probable that the radiation is a mixture of the scattered with the homogeneous rays, the proportional effect of the scattered being greater than in the radiation from Cu, Zn, &c.

*Conclusions.*

Secondary Röntgen rays of two distinct types are emitted by substances subject to a beam of X-rays. One, a scattered radiation produced by the motion of electrons controlled by the electric force in the primary Röntgen pulses, has been dealt with in previous papers by one of us, and has been further discussed in this paper with the H-S group of elements. The other, a homogeneous radiation characteristic of the element emitting it, and produced by the motion of electrons uncontrolled by the electric force in the primary pulses, has been but briefly mentioned.

All the phenomena of secondary X-rays so far observed by us may be explained by means of these two.

The experimental results of these investigations, both on the scattered radiation and the homogeneous radiation, are summarized below. In order to make the summary more complete, we have introduced several results which have been previously published. The references for these are given.

*Experimental Results.*—Scattered X-rays—those produced by the motion of electrons controlled by the primary pulses—constitute the bulk of the secondary radiation from elements of the H-S group when these are subject to a primary beam of low to moderate penetrating power.

Scattered X-rays are also emitted by many elements of higher atomic weight—probably by all—when subject to such a primary beam; but unless the primary is very soft they are accompanied by homogeneous secondary X-rays (characteristic of the radiating element) which produce much greater ionizations.

The law of intensity of these scattered rays which holds for elements of the H-S group—that the intensity of radiation from an atom is proportional to its atomic weight—cannot be extended to include the elements of higher atomic weight. From some elements at least the intensity is greater than would be given by this law.

The scattered radiation from some elements whose characteristic homogeneous radiation is of comparatively penetrating type has been obtained free from admixture with this homogeneous radiation by the use of a primary beam consisting of less penetrating rays than the characteristic secondary.

Those scattered radiations not thus isolated have been accompanied by a homogeneous radiation more easily absorbed than the primary radiation producing them.

We have obtained no conclusive evidence that the relative intensity of secondary scattered and primary radiations changes with the penetrating power of the primary rays.

All elements of atomic weight greater than that of sulphur which have been examined emit a homogeneous secondary radiation when subject to a primary beam of X-rays of ordinary penetrating power. Cr, Fe, Co, Ni, Cu, Zn, Ag, have been examined. All other elements whose secondary radiations have been examined less minutely appear similar in this respect.

The penetrating power of this radiation from each element examined has been found independent of the intensity or the penetrating power of the primary radiation producing it; it is characteristic of the element emitting it.

The penetrating power of this radiation is a periodic function of the atomic weight of the radiating element ( $e$ ).

The ionizing power of this radiation and almost certainly its energy is usually very much greater than that of the scattered radiation.

The homogeneous radiation has invariably been found more easily absorbed than the primary radiation producing it.

In all cases, when a primary was used which was softer than the characteristic homogeneous radiation, this radiation was not emitted. Also there is reason (from the curve connecting absorbability of a secondary radiation and the atomic weight of a radiator) for believing that those elements H-S which do not under ordinary circumstances emit such radiation, possess a characteristic radiation which is more penetrating than any primary beam used.

The intensity of this homogeneous radiation from copper  
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is for a considerable range in the penetrating power of the primary merely proportional to the ionization produced by that primary in a thin film of air and is otherwise independent of the penetrating power of the primary. This is not general, as in many cases—probably all—the homogeneous radiation disappears when the primary radiation becomes more absorbable.

The intensity of the homogeneous rays in a given direction does not depend appreciably on the position of the plane of polarization of primary beam producing them.

The intensity of this radiation in a direction approximately opposite to that of propagation of the primary beam producing it, is within the small errors of experiment equal to that in a direction at right angles (*g*).

This radiation is specially penetrating to the element which emits it and to a less extent to elements of neighbouring atomic weight (*f*).

The fraction of the homogeneous rays from one element—copper—scattered by air, is the same as that for X-rays proceeding direct from an X-ray tube (within experimental errors) (*b*).

The absorbability of the secondary rays from copper which are scattered by air—tertiary rays—is the same as that for the direct secondary (*b*).

### *Theory.*

The theory of the scattered X-rays has been dealt with in various papers, and the experimental evidence in support of that theory—briefly referred to in this paper—is so overwhelming that it need not be further discussed here.

It is important, however, to consider the evidence we have regarding the nature and origin of the homogeneous rays, which are characteristic of the elements emitting them.

The fact that the homogeneous secondary rays from copper are scattered by air in approximately the same proportion as the primary rays proceeding direct from an X-ray tube, and that the absorbability of these scattered rays is the same as that of the direct secondary rays, is strong evidence that they are of the nature of X-rays, for neither the observed intensity, nor the scattering without degradation, would have been expected on any corpuscular theory, whereas they are in perfect harmony with the æther pulse theory.

The relation between the absorption of a mixture of the homogeneous rays from a number of elements by various elements and the atomic weight of those absorbing elements is also very different from that found for any material

radiation, while it is very similar to that obtained by experiments on a beam of Röntgen rays\*.

The special powers of penetrating certain substances are such as have not been observed and are difficult to conceive of on any corpuscular theory.

Neither electrostatic nor magnetic deflexion of these rays has been observed.

Finally, the fact that the homogeneous rays are invariably produced by primary rays of more penetrating type, yet not necessarily more than just on the more penetrating side, appears some of the strongest evidence in favour of similarity in type between the primary and secondary rays. If the natures were different, the penetrating powers would represent totally different physical facts, and such connexion between them would be inconceivable. We can only conclude from consideration of this evidence that the nature of the homogeneous rays is similar to that of the primary X-rays.

As the homogeneous rays are of the nature of Röntgen rays, we must conclude that the radiation is set up by disturbance of electrons produced directly or indirectly by the passage of the primary pulses. That this motion of electrons is not controlled by the electric forces in the primary pulses, is proved by the equality of the intensities of radiation in a direction approximately opposite to that of primary propagation and one at right angles, by the absence of evidence from the secondary rays of polarization of a primary beam in which such polarization exists, and by the absence of dependence of the penetrating power of the secondary beam on that of the primary.

The forces called into play which produce the accelerations resulting in radiation cannot then be directly due to the electric displacement in the primary pulses, but must be those called into play in the atom itself. The two possibilities that suggest themselves are that the radiations result from a disturbance of the atom, which quickly recovers its normal configuration, or that it is produced when the equilibrium of an atomic system is destroyed and forces of unusual magnitude are called into play.

The homogeneity of the radiation and its independence of the primary rays suggest a regularity in the motion which is characteristic simply of the atom; and although the relation between intensity of secondary radiation from copper and ionization produced by the primary in air is striking, it does not follow that the radiation is due to ionization in the

\* Details of these experiments have not been given.

radiating substance. Indeed, this appears highly improbable, for the homogeneous radiation disappears when the primary radiation is made "soft" and appears in great intensity when the primary is "hard."

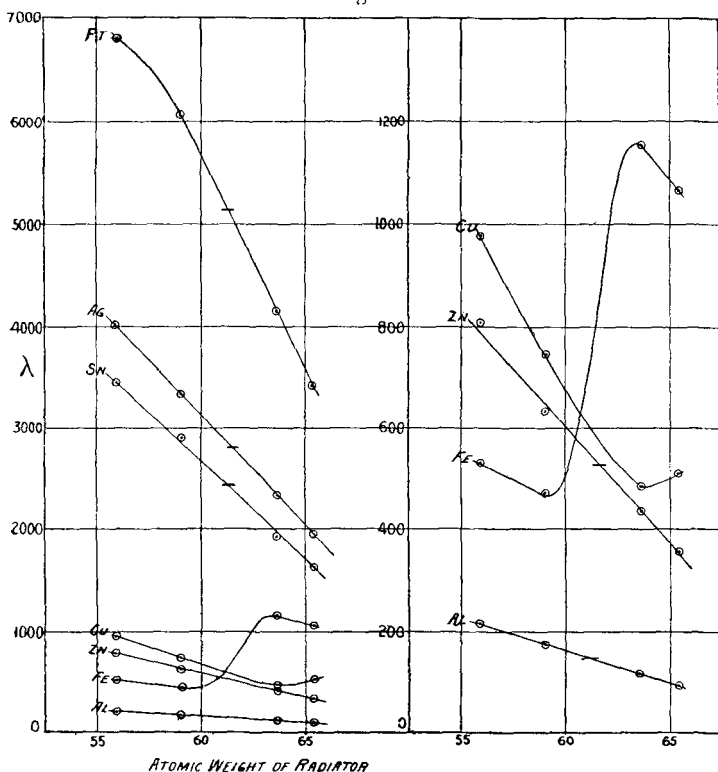
If, then, the radiation were emitted simply during the process of ionization and were proportional to it, a soft primary radiation would produce little or no ionization and a more penetrating radiation—(that is one more penetrating to most substances)—would produce an ionization at least hundreds of times as great. Though experiments have not been made on the ionizations produced in these substances investigated, such variations in ionization are of a higher order of magnitude than any observed. Again, ionization is undoubtedly produced in substances of the H-S group of elements when homogeneous rays are not emitted in appreciable intensity. We, however, do not know anything of the homogeneous rays from these substances except that they are probably of penetrating type.

The relation between the absorption of a primary radiation and the intensity of secondary radiation emitted by the absorbing substance, also shows that the emission of homogeneous radiation necessitates a special absorption of the primary beam. Also, as far as we can estimate from experiments made, the energy of the homogeneous radiation is more than accounted for by the special absorption necessary to the production of that radiation.

Thus in fig. 4 we have plotted the coefficients of absorption of rays from Fe, Co, Ni, Cu, and Zn by Al, Zn, Ag, Sn, Pt. In each case the radiations absorbed are not—if we generalize from results given—capable of stimulating a homogeneous radiation characteristic of the absorbing substance, because these are of more penetrating type. The curves are similar. But when iron is used as the absorbing substance, cobalt radiation, which is just more penetrating, is unable to produce more than a feeble secondary in the iron, so the decline of the line for Fe is not quite so great as would have been expected, because of the little extra absorption necessary to set up this slight radiation from iron. The copper radiation, which is much more penetrating, is able to stimulate an intense radiation in iron and at the same time is enormously absorbed. This is exhibited by the sudden rise in the Fe curve. Beyond copper, the absorption appears to fall again according to the usual law, the absorption of the zinc radiation being a little less than that of the copper radiation. The stage is thus reached when the change in the penetrating power of the primary radiation produces no difference in the relative amounts of

secondary homogeneous radiation and ionization by the primary beam, as shown by fig. 2 for the copper radiation. A study of the curves (fig. 3), exhibiting the transparency of various metals to homogeneous rays, shows the same thing. Thus, dealing with the radiation from zinc, aluminium, in which a Zn radiation does not stimulate, a homogeneous

Fig. 4.



secondary radiation is fairly transparent. Iron, in which an intense radiation is set up—the characteristic radiation from iron being considerably softer than that from zinc—is very opaque. Copper is much more transparent, as the zinc radiation being only a little more penetrating, is only able to set up a feeble radiation; while zinc, in which zinc radiation is unable to set up any further radiation, is more transparent still. The substances Ag, Sn, and Pt appear relatively more transparent to this radiation than to a more penetrating beam\*.

\* Also Phil. Mag. Sept. 1907, p. 416, fig. 5.



The zinc radiation is unable to set up radiations in these elements, as they are of more penetrating type. The absorptions are, however, not sufficiently abnormal to speak of with certainty. The effect is more clearly shown by the curve obtained from the homogeneous radiation from silver (fig. 3).

These results show that a substance whose characteristic radiation is equally or more penetrating than the radiation incident upon it, does not absorb that radiation so much as when the incident is of more penetrating type and able to stimulate a secondary radiation in that substance. As the penetrating power of the incident radiation (as measured by most substances) increases, the absorption increases up to a certain point. A definite portion of the absorption thus appears to be connected with the secondary radiation, and may be proportional to it. But this does not conclusively show that ionization, or some kind of disruption in the atom is not the cause of the radiation, for the absorption of a certain amount of energy of the primary beam might be required to produce the instability which liberates more energy.

The facts that the homogeneous rays have invariably been found more easily absorbed than the primary rays producing them, and, in the cases investigated, that the homogeneous rays disappear when the primary becomes more easily absorbed, indicate a relation between primary and secondary which would be difficult to explain if this radiation were directly due to a disruption of any kind taking place in the atom. It appears rather that the radiation is due to what may be regarded as quite a normal behaviour of an atom after it has been passed over by Röntgen pulses, such as a free vibration of electrons.

Let us consider the passage of an electromagnetic pulse, in which the electric field is undirectional, over an electron with a free period of vibration much longer than double the time taken for the pulse to pass over it. (In this case the Röntgen pulse is thinner and more penetrating than the half-wave produced by the free vibration of the electron.) The electron receives an impulse and is left with kinetic energy after the pulse has passed. Consequently it is then acted upon by forces called into play in the atom itself. These produce a motion which is characteristic of the atom of which the electron forms a part, and this results in radiation—probably the homogeneous radiation discussed in this paper.

When the thickness of the primary pulse approaches the half-wave length characteristic of the vibratory motion of the electron in the atom, the restoring force in the atom is brought

into play before the primary pulse has passed and the absorption of energy and energy of subsequent radiation are diminished. This explains the diminished radiation when the penetrating power of the primary decreases and approximates to that of the radiation characteristic of the radiating substance. When the primary pulse is thicker than the half-wave characteristic of the motion of the electron, the electron is displaced a short distance and is gradually brought back by the restoring force against a gradually weakening electric force in the primary pulse, so that when this has passed, the electron is near its position of equilibrium again and the motion and radiation produced in the other cases are now absent. It is impossible to give an exact solution without some knowledge of the distribution of electric force in the primary pulses, of the forces binding the disturbed electron to the rest of the atomic system, and of the structure of that system; but we may consider this to be an approximation to the behaviour of each electron directly concerned with the phenomena discussed. The number of such electrons may not exceed one in each atom of radiating substance.

According to this theory, energy is taken from the primary beam and part, at least, appears as secondary homogeneous radiation, the rest being transformed into heat.

As the energy of this radiation is quite a considerable fraction of the total energy absorbed, we should expect that the difference between absorptions of primary rays more or less penetrating than the radiation characteristic of the absorbing element would be evident from a study of the absorption of the various homogeneous beams. But we have seen that there is a large absorption of a homogeneous radiation by an element which emits a much more easily absorbed radiation, because much of the energy is given to the electrons; that for other elements which emit a radiation only slightly softer, the absorption is much diminished because only a feeble disturbance and consequent secondary radiation is set up in the absorber; and when the radiation characteristic of the absorbing substance is more penetrating than the absorbed radiation, the absorption is small and no homogeneous secondary radiation is produced. Thus what we have previously referred to as the special penetrating power of the homogeneous radiations may be explained by the small displacement produced in an atom by a radiation more easily absorbed, equally absorbed, or slightly more penetrating than the radiation characteristic of that atom, for reasons indicated.

Though according to such a theory, if the displaced electrons

were merely held by a body of much greater mass, we should expect the emission of wave-trains instead of pulses, yet if the atomic system consisted of a number of interacting electrons, the energy of vibration would be rapidly communicated to other parts of the system and the motion of the displaced electron would be little more than half a complete vibration. The resultant radiation would in that case behave much as a number of isolated pulses.

An explanation on the disruption theory would be similar in many respects, but the displacement of electrons would on such a theory be sufficient to destroy the equilibrium of the atomic system and produce some change in its structure. The evidence against this is perhaps not conclusive, but there is no indication from the energy of secondary X-radiation of such a phenomenon, and the relation between the primary and secondary radiations points rather to the latter being due to the motion of the atomic system in regaining its normal configuration.

George Holt Physics Laboratory,  
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30th May, 1908.

#### ***XLIX. The Amount of Radium Emanation in the Atmosphere.***

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**I**N 1900 Elster and Geitel † found that when a negatively electrified wire was exposed to the atmosphere for some time a radioactive deposit was formed on it whose properties agreed very closely with the properties of the active deposit from radium. Blanc ‡ and others have shown that a thorium deposit accompanies the radium deposit, the relative amounts of the two deposits being dependent on the time of exposure of the wire. Eve § compared the amount of the active deposit obtained from a known volume of air with the active deposit obtained from the emanation generated by a solution of radium bromide of known strength, and in this way formed an estimate of the amount of radium necessary to keep up the supply of emanation. Strutt ||, Eve ¶, July \*\*

\* Communicated by Prof. J. J. Thomson, F.R.S.

† Elster and Geitel, *Phys. Zeit.* ii. 1901.

‡ Blanc, *Phil. Mag.* Mar. 1907. Also Dadourian, *Le Radium*, April 1908.

§ Eve, *Phil. Mag.* July 1905.

|| Strutt, *Proc. Roy. Soc.* May 1905, May and Aug. 1906.

¶ Eve and MacIntosh, *Phil. Mag.* Aug. 1907.

\*\* July, *Phil. Mag.* Mar. 1908.