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[F O U R T H S E R I E S .]

ART. XXIX.—*On the Corpuscular Rays produced in different Metals by Röntgen Rays*; by C. D. COOKSEY.

SAGNAC* has shown that when Röntgen rays fall on a substance this substance gives off rays very like the Röntgen rays producing them. Barkla† has investigated these rays and found that those from gases and light solids were almost identical in penetrating power with the primary rays producing them, while those from heavy solids such as lead, zinc, copper, etc., are much less penetrating than the primary. He also finds that the rays from gases and light solids vary in penetrating power as the primary varies, but those from the heavy solids vary very little for a large variation in the penetrating power of the primary. All these secondary rays are probably pulses in the ether like Röntgen pulses, though the secondary pulses may vary greatly in thickness from the primary producing them; heavy metals giving out much thicker pulses than the primary. Hereafter in referring to this type of rays we shall speak of it as "Secondary Röntgen Rays."

Beside this type of rays, Townsend,‡ Dorn,§ and Curie and Sagnac|| have shown that heavy metals, when Röntgen rays fall on them, give out a very absorbable type of radiation, consisting in part of negatively charged particles. The velocity of these particles is of the order of that of the cathode particles in a highly exhausted tube. Bestelmeyer¶ has investigated by a photographic method the corpuscular rays produced when Röntgen rays fall on a platinum plate and found that they have velocities from 0.195 to 0.327 of the velocity of light. He shows

* Annales de Chimie et de Physique, xxii, p. 493, 1901.

† Phil. Mag., xi, p. 812, 1906.

‡ Proc. Camb. Phil. Soc., x, p. 217, 1899.

§ Abhand. d. naturf. Ges. zu Halle, xxii, p. 39, 1900.

|| Journal de Physique (4), i, p. 39, 1902.

¶ Ann. der Physik, xxii, p. 429, 1907.

that the velocity does not depend at all on the intensity, but does depend on the penetrating power of the primary Röntgen rays producing them; the harder or more penetrating primary rays producing higher velocities in the corpuscular rays. From some results published by Prof Bumstead* on the heating effects produced when Röntgen rays are absorbed by different metals, I was led to investigate this last type of rays, which

we shall refer to as "Corpuscular Secondary Rays." with a view to determining the relative number produced in different metals for equal absorptions of the same beam of Röntgen rays.

Apparatus.

It was decided to investigate these corpuscular secondary rays by means of the ionization which they produce, but owing to the great ease with which they are absorbed it was found that the thinnest aluminium which could be obtained would stop all but a few of these rays. It was necessary, therefore, to

* This Journal, xxi, Jan., 1906.

let the metal to be examined form one end of the ionization chamber, and let the primary beam of Röntgen rays pass through the ionization chamber and fall on the metal. Then all the corpuscles coming from the metal would pass into the ionization chamber, producing ions in the air, and if the ionization due to the Röntgen rays was known, that due to the corpuscular secondary rays could be deduced. But it was found that the ionization due to the secondary rays was such a small fraction of that due to the primary, that this method was not accurate.

The apparatus as finally used and shown in fig. 1 was designed to eliminate the ionization due to the primary rays. Two ionization chambers, "A" and "B," were used, consisting of hollow brass cylinders about 5^{cm} long and about 10^{cm} in diameter, each encased in thick lead. The cylinders were mounted on vulcanite insulators, "f," with their axes in a horizontal plane and parallel to each other and about 14^{cm} apart. Above the cylinder "A" and supported on it was a gold leaf electroscope consisting of a lead box, "a," with windows for observing the gold leaf, and a narrow strip of gold leaf hung from the upper end of a vertical brass rod, "b." The brass rod, "b," passed through the bottom of the electroscope box into the interior of "A," being insulated from "A" and "a" by vulcanite rings, "f," and its lower end terminating in a ring, "c," about 4^{cm} in diameter, made of fine brass wire. This ring was placed concentric with the axis of "A" and in a vertical plane parallel to and midway between the ends of "A." A brass rod, "g," insulated from "A" and "B" by vulcanite rings, "f'," connected "c" to a similar ring, "c'," similarly placed with respect to "B."

The Röntgen ray bulb was about 60^{cm} in front of the two ionization chambers with its target midway between their axes, so that the beam would pass through each cylinder longitudinally. The ends of "A" and "B" on the side toward the tube were covered with very thin aluminium leaf, and the rear end of "B" was covered in a similar manner. The rear end of "A" was left open, but provided with clamps by means of which disks of the metal to be tested could be clamped over this end.

Both cylinders stood in a thick lead box, open at the rear, and provided with windows in the side for observing the electroscope. In the front of the box were two circular openings, "W" and "W'," corresponding respectively with the ends of "A" and "B." Both openings were just small enough to prevent the beam of Röntgen rays from falling on the walls of either cylinder. Lead screens with different sized holes

bored in them could be hung in front of "W" to control the amount of rays entering "A." A shutter, "d," placed over "W" and controlled by a screw "e," gave a very fine adjustment to the size of this opening.

In use the lead box, chamber "A," and electroscope case were all connected to earth; the chamber "B" was kept at a constant potential of about 400 volts, and the gold leaf, rings "c" and "c'," and connections were brought initially to about 200 volts. This made a difference of potential between "A" and "c" of 200 volts, and between "B" and "c'" of minus 200 volts. The fall of the gold leaf due to the ionization in the chamber "A" could be read with a microscope having a micrometer eyepiece. If the Röntgen rays were turned on, and the size of the opening, "W'," properly adjusted so that there should be the same amount of ionization in "B" as in "A," the flow of electricity from "c" to "A" would be just equal and opposite to the flow from "B" to "c'," and there would be no motion of the gold leaf. In this way the ionization due to the Röntgen rays and any natural leak could be eliminated.

In order to test a given metal, a disk of the metal was made to fit over the rear end of the chamber, "A." This disk was then clamped over the end with a thin disk of aluminium interposed between it and the primary rays. (Aluminium was used because it gives off hardly any of the corpuscular secondary rays, and there do not enough of the secondary Röntgen rays come off from a thin sheet to produce any appreciable ionization.) The Röntgen tube was then excited, and the shutter, "d," adjusted till there was no motion of the gold leaf. The aluminium screen was then removed, and the time taken for the gold leaf to fall over a given number of scale divisions measured. The fall of the gold leaf was then due to the ionization produced by the secondary rays alone from the metal.

Preliminary experiments showed that an appreciable amount of the ionization in the chamber, "A," was due to secondary rays of the Röntgen type, and it was therefore necessary to find what proportion of the ionization was due to corpuscular secondary rays, and what due to secondary Röntgen rays. For this end the absorption of the secondary rays in thin sheets of aluminium leaf was measured. The primary rays were first eliminated by balancing the apparatus with a sheet of aluminium over the metal about 1^{mm} thick, sufficient to stop all the secondary rays from the metal, but not thick enough to give off any appreciable secondary rays itself that would be absorbed in the ionization chamber. The ionization was then measured which was due to the secondary rays from the bare metal and to those which got through successive sheets of

aluminium leaf about $\cdot 001^{\text{mm}}$ thick. Curves were then plotted, having for abscissae the thickness of aluminium in millimeters, and for ordinates the ratios of intensity of ionization after absorption to the intensity before absorption.

Since the penetrating power of the secondary rays depends upon that of the primary rays, it was necessary to keep the Röntgen ray tube very constant, and to have some standard of the penetrating power of the primary rays. A self-adjusting tube was used which was found to be fairly constant. The standard of penetrating power or hardness of the primary rays was arbitrarily taken as the ratio of the ionization produced by the rays after passing through a sheet of aluminium $0\cdot 82^{\text{mm}}$ thick to that produced by the unobstructed rays. This ionization was measured in the chamber, "A," after connecting the chamber, "B," to earth, and entirely closing the opening, "W'." The hardness of the primary rays was varied by varying the length of the spark gap in the regulator, and by filtering out the soft rays by a thin iron screen.

Absorption curves were plotted for the secondary rays from lead, zinc, nickel, copper, tin, and silver for two different degrees of hardness of the primary rays. In the case of lead four curves were plotted for four different hardnesses of the primary rays. The curves are represented by the full lines passing through the circles and crosses. In every case the circles represent rays produced by soft, and the crosses rays by hard, primary rays. The following tables give the data from which the curves were plotted. Tables 1 and 2 refer to lead, 3 to zinc, 4 to copper, 5 to nickel, 6 to tin, and 7 to silver.

TABLE I.

Hardness=0.62				Hardness=0.89		
I	II	III	IV	II'	III'	IV'
0	1.00	1.00	0	1.00	1.00	0
0.001	0.29	0.22	-0.66	0.49	0.45	-0.35
0.002	0.15	0.07	-1.15	0.24	0.19	-0.72
0.003	0.10	0.02	-1.70	0.11	0.06	-1.22
0.004	0.09	0.01	-2.00	0.08	0.03	-1.52
0.008	0.07	--	--	0.03	--	--

TABLE II.

Hardness=0.61				Hardness=0.95		
I	II	III	IV	II'	III'	IV'
0	1.00	1.00	0	1.00	1.00	0
0.001	0.32	0.24	-0.62	0.44	0.40	-0.40
0.002	0.19	0.11	-0.96	0.25	0.21	-0.68
0.003	0.12	0.03	-1.52	0.12	0.11	-0.96
0.004	0.10	0.02	-1.70	0.09	0.04	-1.40
0.008	0.07	--	--	0.02	--	--

TABLE III.

Hardness=0.66				Hardness=0.97		
I	II	III	IV	II'	III'	IV'
0	1.00	1.00	0	1.00	1.00	0
.001	0.55	0.31	—0.51	0.49	0.41	—0.39
.002	0.45	0.16	—0.80	0.33	0.19	—0.72
.003	0.37	0.05	—1.30	0.20	0.08	—1.10
.004	0.38	0.03	—1.52	0.21	0.04	—1.40
.008	0.29	--	--	0.11	--	--
.012	0.26	--	--	0.09	--	--

TABLE IV.

Hardness=0.68				Hardness=0.78		
I	II	III	IV	II'	III'	IV'
0	1.00	1.00	0	1.00	1.00	0
.001	0.42	0.23	—0.64	0.52	0.44	—0.36
.002	0.33	0.11	—0.96	0.29	0.19	—0.72
.003	0.29	0.07	—1.15	0.19	0.07	—1.15
.004	0.29	0.04	—1.40	0.23	0.03	—1.52
.008	0.23	--	--	0.10	--	--
.012	0.22	--	--	--	--	--

TABLE V.

Hardness=0.64				Hardness=0.82		
I	II	III	IV	II'	III'	IV'
0	1.00	1.00	0	1.00	1.00	0
.001	0.45	0.24	—0.62	0.33	0.32	—0.49
.002	0.40	0.11	—0.92	0.24	0.14	—0.85
.003	0.33	0.05	—1.30	0.13	0.04	—1.40
.004	0.30	0.02	—1.70	0.10	0.01	—2.00
.008	0.24	--	--	0.09	--	--
.012	0.19	--	--	--	--	--

TABLE VI.

Hardness=0.59				Hardness=0.95		
I	II	III	IV	II'	III'	IV'
0	1.00	1.00	0	1.00	1.00	0
.001	0.41	0.39	—0.41	0.50	0.43	—0.37
.002	0.18	0.15	—0.82	0.29	0.19	—0.72
.003	0.11	0.05	—1.30	0.19	0.08	—1.10
.004	0.04	0.02	—1.70	0.14	0.03	—1.52
.008	0.04	--	--	0.11	--	--
.012	--	--	--	0.10	--	--

TABLE VII.

Hardness=0.60				Hardness=0.90		
I	II	III	IV	II'	III'	IV'
0	1.00	1.00	0	1.00	1.00	0
.001	0.44	0.37	—0.43	0.52	0.41	—0.39
.002	0.17	0.10	—1.00	0.26	0.16	—0.80
.003	0.14	0.04	—1.40	0.20	0.07	—1.15
.004	0.12	0.02	—1.70	0.17	0.04	—1.40
.008	0.11	--	--	0.13	--	--
.012	0.09	--	--	0.12	--	--

Column I of the tables gives the thickness of aluminium in millimeters; columns II and II' give the intensity of the secondary rays after passing through the corresponding thickness of aluminium for the two hardnesses respectively, the intensity of the rays from the bare plate being always taken as unity.

In all the curves there is a very sudden drop up to the first three or four sheets of aluminium, and then the curves fall off more slowly. The first part of the curve up to the first three or four sheets of aluminium is undoubtedly due, for the most part, to the corpuscular secondary rays, while beyond this point the corpuscular rays are practically all absorbed and there remain only the secondary rays of the Röntgen type. As has been said before, these corpuscles come off with velocities comparable with the velocities of the cathode particles in a highly exhausted tube; say between 10^9 and 10^{10} cm./sec. Seitz*

has investigated the absorption of cathode rays driven by 20,000 volts, corresponding to about 9×10^{10} cm./sec., and finds that they will penetrate aluminium about .002 mm thick, the fraction which gets through being about 0.16. A little further on we shall show that this is about the order of absorption for the rays constituting the first part of the curves under discussion. It is this agreement which leads us to believe that the first part of the curves is largely due to the corpuscular secondary rays.

With the exception of zinc and nickel the first part of all the curves due to the secondary rays produced by the hard primary rays lies above those produced by the soft primary rays. This would be expected from the results of Bestelmeyer, before mentioned, where the corpuscles produced by harder primary rays had higher velocities than those produced by the softer

* Annalen der Physik, xii, p. 860, 1903.

primary rays. The fact that in the case of lead and copper the curves cross each other, and that in the case of zinc and nickel the harder lies below the softer, would seem to show that for these metals the harder primary rays produced less penetrating secondary rays. But there are several reasons to account for this. In the first place, for zinc, nickel, and copper a comparatively large proportion of the secondary rays consists of those of the Röntgen type which are much more penetrating than the corpuscular rays, and in the case of lead there is an appreciable quantity of these rays present. Owing to the shortness of the ionization chamber, "A," a considerable proportion of the secondary Röntgen rays doubtless passed entirely through the chamber, producing very few ions. If now the hard primary rays produce secondary rays of the Röntgen type more penetrating than those produced by the softer primary rays, a *larger* proportion of these penetrating secondary rays would pass through the chamber, without producing ions, than of the less penetrating ones. Thus the less penetrating rays would produce more ionization, and the curve corresponding to them would lie higher than the curve corresponding to the more penetrating secondary rays. This reasoning would not apply to the corpuscular secondary rays, since the most penetrating of these are absorbed by a few millimeters of air. But in all but two cases the part of the curve corresponding to the corpuscular rays shows greater penetration when the corpuscles are produced by hard primary rays than by soft. In the two exceptions, namely zinc and nickel, there are so many of the Röntgen type of secondary rays present that they would obscure the effect of the corpuscular type, and the above reasoning would again apply.

In order to show more clearly the variation of penetrating power of the corpuscular secondary rays for different hardnesses of the primary, I have subtracted from the whole curve the amount, shown by the broken straight lines, which seems to be about the proportion of secondary *Röntgen* rays present; and again plotted the curves after reducing the initial intensity to unity. These are shown by the broken curved lines. The intensities are given in columns III and III' of tables 1 to 7. In every case the curve corresponding to hard primary rays lies above that for the soft, except in nickel and copper, where they cross very near the last point. This is probably due to not allowing enough for the secondary Röntgen rays.

If we consider the amount of the rays left unabsorbed after passing through $\cdot 002^{\text{mm}}$ of aluminium, as shown by these latter curves, it is found to be between 0.10 and 0.20 of the total amount of corpuscular rays coming off. This agrees very well with the absorptions found by Seitz for cathode rays of high

velocity, and leads us to believe, as mentioned above, that we are dealing with corpuscular secondary rays of velocities comparable with those measured by Seitz.

In subtracting the secondary Röntgen rays, where the points lie badly off the curve, the curve was taken in preference to the point. Attention should be called to the points for zinc and copper corresponding to the intensity of the rays after passing through four sheets of aluminium. These points lie as high or higher than the corresponding ones for three sheets, and it is due in all probability to an error in measuring the thickness of the fourth sheet of aluminium. A different sheet was used for the other metals, but I have not had time to repeat the two curves in question.

An attempt was made to see if the absorption of the corpuscular rays followed an exponential law. To this end the common logarithms of the points (given in columns III and III' of the tables) were plotted. The origin was taken at the point on the axis of ordinates corresponding to unit intensity of the secondary rays, and the logarithms of the intensity plotted down, each tenth division for the intensity being equal to two tenths for the logarithms. The values of the logarithms are given in columns IV and IV' of the tables.

For the more penetrating primary rays the points all lie pretty well on the straight line passing through the origin. This would seem to show that the corpuscular secondary rays produced by hard primary rays were very homogeneous in regard to velocities and were absorbed according to an exponential law. When we come to consider the soft rays we find that if we neglect the origin, the points lie fairly well on a straight line which cuts the axis of ordinates below the origin. This in connection with the absorption curves for the corpuscular rays leads us to the conclusion that the soft primary rays give rise to corpuscular rays between 70 per cent and 80 per cent of which are slow moving corpuscles which are almost all absorbed in the first $\cdot 001^{\text{mm}}$ of aluminium, and the rest faster moving corpuscles which are absorbed according to an exponential law; but in all cases, except nickel and copper, these corpuscles are slower moving than those produced by the hard primary rays. These exceptions, I am inclined to think, are again due to not taking sufficient account of the secondary Röntgen rays present.*

In the case of tin and silver the points for the rays produced by the soft primary rays lie on a straight line passing through the origin, showing that the corpuscular rays from these metals are very homogeneous even though produced by soft primary rays.

* The writer hopes to investigate this question further by using a shorter ionization chamber.

TABLE VIII.

	0	·001	·002	·003	·004	·008	·012
I	3·4	6·8	1·8	2·6	3·8	4·8	5·2
II	3·8	7·8	2·0	2·8	3·4	5·0	5·4
III	4·0	7·6	2·0	3·2	4·4	5·8	6·6
Average	3·73	7·40	1·93	2·86	3·86	5·2	5·7
Ratio	1·00	0·50	0·29	0·19	0·14	0·11	0·10

Table 8 has been inserted to give an idea of the actual observations as taken. It is for tin for a hardness of the primary rays of 0·95. The numbers in the top row give the thickness of aluminium in millimetres. The next three rows give the three sets of observations of the time in seconds for the gold leaf to fall over a constant number of scale divisions; these values being inversely proportional to the intensity of ionization. The gold leaf moved so rapidly for the unabsorbed rays and so slowly after the rays had been partially absorbed that the same number of scale divisions could not be used for all thicknesses of aluminium. The times in the first two columns are for a fall of forty scale divisions, while in the remaining five columns the times are for a fall of five scale divisions from the same zero point. A separate observation showed that for a constant intensity of ionization the fall for forty divisions was to the fall for five in the ratio of 6·7 to 1. The last row gives the ratio of intensity of ionization to the initial intensity after reducing the times of fall to the same number of scale divisions. It was found that owing to asymmetry of the apparatus a very small change of hardness in the primary rays would disturb the balance enough to account for a large part of the errors, though great care was taken to see that the ionization due to the primary rays was properly balanced out before each separate observation. To show the magnitude of this error, suppose that the time observed for the secondary rays to produce a fall of five scale divisions was five seconds, it was sometimes found that after an observation the balance had been disturbed sufficiently for the primary rays alone to produce a fall one way or the other of five divisions in eighty seconds, which would tend to make the fall observed for the secondary rays too large or too small by about 6 per cent.

After this investigation of the character of the secondary rays coming off from different metals, the way was open to obtain some idea of the relative number of corpuscles produced in different metals for equal absorptions of the primary Röntgen rays. The method of procedure was nearly the same as that already described. The absorption curves showed that essentially all the corpuscles were stopped in the first ·003^{mm} to ·004^{mm} of aluminium, while practically all the secondary

Röntgen rays were able to get through. In order to compare two metals, say lead and zinc, the lead was covered with about $\cdot 004^{\text{mm}}$ of aluminium and clamped to the chamber, "A". The Röntgen rays were then turned on and the leak balanced as before; but this time not only was the ionization due to the primary rays eliminated, but also that due to all the secondary Röntgen rays which got through the aluminium. After the system was balanced, the aluminium was removed, and the ionization measured which was due to all the copuscular secondary rays which escaped from the lead. Then the zinc was tested in the same way, care being taken to keep the intensity and hardness of the primary rays constant throughout the comparison. This method was pursued with all the metals; lead was taken as the standard, and all the other metals compared to it separately in order that the intensity and hardness of the primary rays might be the same throughout the comparison. Hardnesses were used as nearly as possible the same as those used in the first experiments.

It might be well here, by the way of parenthesis, to give some idea of the hardness of the tube used. The softest rays obtainable were those equal to a hardness of about 0.4 in the arbitrary scale, the vacuum being down to about the point where Röntgen rays begin, the green fluorescence on the walls of the tube just beginning to show. It was found impossible to keep the tube as constant as necessary with so low a vacuum, the vacuum changing very rapidly at this point; therefore a hardness of about 0.6 was the softest used, and this could be kept very constant. A thin iron screen was always used when hard rays were wanted, but this does not really make the rays harder, only cutting out the softer pulses in the beam, and making the *proportion* of hard pulses greater. As well as using the iron screen, the tube was run for a while with a longer spark gap in the regulator and with higher potential from the coil. This did make the rays harder, as the cathode particles producing them traveled faster in the tube.

To resume: the above comparison of different metals gave only the relative ionization due to the corpuscles which escaped from the metals, but not the number of corpuscles produced in the metal by the primary Röntgen rays. This latter can be roughly calculated as follows:

The intensity of the primary rays after passing through a thickness x of the metal, if we assume that for thin layers the rays are absorbed exponentially, is $I_0 e^{-\lambda x}$, where λ is the coefficient of absorption of the primary rays in the metal. The number of corpuscles produced per cm. of path of the primary rays is proportional to the intensity of the primary. The number produced in a layer of the metal between x and $x + dx$ is pro-

portional to $I_0 e^{-\lambda x} dx$. If k' be the coefficient of absorption of the corpuscular rays in the metal, the number which emerge from this layer will be proportional to $I_0 e^{-\lambda x} e^{-k' x} dx$, and if we call the total number of corpuscles emerging from the metal N' , we have that

$$N' \propto I_0 \int_0^{\infty} e^{-(\lambda+k')x} dx \\ \propto \frac{I_0}{\lambda+k'}$$

If we let the total number of corpuscles generated in the metal be N , then

$$N \propto I_0 \int_0^{\infty} e^{-\lambda x} dx \\ \propto \frac{I_0}{\lambda}$$

Therefore

$$N \propto \frac{\lambda+k'}{\lambda} N'$$

or

$$\propto \left(1 + \frac{k'}{\lambda}\right) N'$$

Since the corpuscular rays are much more easily absorbed than the Röntgen rays producing them, the quantity $\frac{k'}{\lambda}$ will be very large compared to unity, and we can say

$$N \propto \frac{k'}{\lambda} N'$$

N' is not, however, directly proportional to the intensity of the ionization measured in the ionization chamber. To find what relation the ionization measured bears to N' we must take into consideration the absorption of the corpuscles in air, and the number of ions produced by a corpuscle per cm. of path for different velocities. For the range of velocities encountered in these experiments, however, I think we are justified in assuming that the corpuscles from all the metals produce the same specific ionization, for the following reason.

Durack* has measured the specific ionization produced by Lenard rays having velocities of about 4×10^{10} cms./sec., and that produced by the deflectible Becquerel rays having velocities of from 2.4×10^{10} to 2.8×10^{10} cms./sec. In the first case he finds the specific ionization equal to about 0.4 and, in the second, to about 0.17 ions per corpuscle per cm. of path; a fall of about

* Phil. Mag. (6) iv, 29, 1902; and v, 550, 1903.

57 per cent for an increase of velocity of about 78 per cent. Considering the slight variation in velocity with which the corpuscles come off from the different metals in our experiments, as shown by the variation in absorption, it seems safe to assume that the specific ionization due to the corpuscles from the different metals under consideration is approximately the same for all the metals.

To find the relation between N' and the ionization measured let n be the number of ions produced by one corpuscle per cm. of path, and let K be the coefficient of absorption in air for the corpuscles from any metal. Then the number of ions produced in a layer of air between x and $x+dx$ is $n N' e^{-Kx} dx$, and the total number of ions produced is

$$n N' \int_0^{\infty} e^{-Kx} dx = \frac{n N'}{K}$$

This is proportional to the quantity measured, say Q . Therefore

$$N' \propto \frac{K Q}{n}$$

In comparing the number of corpuscles produced in any metal with the number produced in lead, we have:

The ratio of the number of corpuscles produced in any metal to the number produced in lead for equal absorptions and equal intensities of the primary rays is equal to

$$\frac{\frac{k'}{\lambda} K Q}{\frac{k'_l}{\lambda_l} K_l Q_l} = \frac{N}{N_l}$$

The coefficient of absorption for the corpuscular rays in passing through any substance is proportional to the density of the substance. We have found the absorption of the corpuscular rays in aluminium; let the coefficient of this be called k . Let ρ be the density of any substance, and ρ' the density of aluminium; then the above reduces to

$$\frac{N}{N_l} = \frac{\lambda_l k^2 \rho}{\lambda k_l^2 \rho_l} \frac{Q}{Q_l}$$

The values of λ were measured for the different metals used. The values of k for the different metals are proportional to the slopes of the straight lines plotted with the curves in the cases where the lines pass through the origin. In the case of the secondary rays produced by the soft primary rays, where the straight lines do not pass through the origin, the following method for finding k was used. The slope of the straight line

passing through the origin and the first point was multiplied by the percentage of rays absorbed by the first layer of aluminium, and the slope of the line passing through the first and remaining points was multiplied by the percentage of rays remaining unabsorbed by the first layer, and the sum of the two numbers thus found divided by 100. This seems to me to give the fairest value of k when the rays are not homogeneous.

TABLE IX.

Metal	Hard	k	$\frac{\rho}{\rho_l}$	$\frac{\lambda_l}{\lambda}$	$\frac{k}{k_l}$	$\frac{k^2}{k_l^2}$	$\frac{Q}{Q_l}$	$\frac{N'}{N'_l}$	$\frac{N}{N_l}$
Lead	0.61	5.9	1.00	1.00	1.00	1.00	1.00	1.00	1.00
"	0.92	3.7							
Silver	0.52	4.6	0.93	2.0	0.78	0.61	0.52	0.41	0.59
"	0.90	3.8							
Nickel	0.59	5.5	0.79	1.4	0.93	0.87	0.36	0.33	0.35
"	0.94	4.9							
Tin	0.59	4.2	0.65	1.1	0.71	0.51	0.64	0.55	0.23
"	0.95	3.6							
Zinc	0.66	4.5	0.63	1.5	0.76	0.58	0.41	0.31	0.22
"	0.80	3.7							
Copper	0.63	5.5	0.79	1.3	0.93	0.87	0.39	0.36	0.35
"	0.82	3.7							

Table 9 gives the values of the ratios of the different quantities in the formula. The absolute values of k , given in the second column, are not the true coefficients of absorption, but the absorption per 0.01^{mm} of aluminium calculated from the common logarithms and not the natural logarithms; but as k comes into the formula only as a ratio, the other constants cancel. The numbers after the metals in the first column denote the hardness of the primary rays used on the metal and on lead when the two were compared. The seventh column gives the ratio of intensity of ionization produced by the corpuscular secondary rays from the different metals to that which was due to the rays from lead, as measured experimentally for the different hardnesses given. The numbers in the eighth column are the ratios of the number of corpuscles which get out of the different metals to those which get out of lead. The numbers in the last column of the table represent the ratios of the total number of corpuscles produced in the metals to the number produced in lead for equal absorptions of the primary rays of equal intensity, as calculated from the formula.

It will be seen at once that, in all cases, this ratio is larger for the harder primary rays, in fact in silver the harder primary rays produce more corpuscles than in lead. For both hard

and soft primary rays fewer corpuscles are produced, the less dense the metal. In the case of copper and nickel, which have the same density, the ratios are the same in the case of the soft primary rays; for the hard primary rays the ratio is much smaller for copper than for nickel, but it will be noticed that the hardness of the primary rays used on copper was considerably less than for the rays used on nickel. In the case of tin and zinc, which have nearly the same density, and on which primary rays of nearly the same hardness were used, we find the corresponding ratios nearly equal. In the case of silver, which is only slightly *less* dense than lead, there are much fewer corpuscles produced than in the lead by the soft primary rays, but the hard primary rays seem to produce more in the silver than in the lead.

It will be noticed in the case of nickel, zinc, and copper for the hard primary rays, and in silver for both soft and hard rays, that N/N_i is larger than N'/N'_i . This means that of the total number of corpuscles produced a less proportion escapes from these metals than from lead, which would not be expected since the corpuscles should be more absorbed in lead, owing to its greater density, than in the other metals. But reference to the values of $\frac{\lambda_i}{\lambda}$, the ratio of the absorption of the primary rays in lead, to that in the other metals, will show that the hard, and in the case of silver also the soft, primary rays are absorbed to a much greater extent in the lead than in the above mentioned metals; while the corpuscular rays coming from lead for hard primary rays possess nearly the same penetrating power as those from zinc and copper, and greater penetrating power than those from silver and nickel, as can be seen from the values of k/k_i . Therefore for equal absorptions of the primary rays the corpuscles must be produced much nearer to the surface in lead than in the other metals, and consequently a greater proportion of the number produced will escape from the lead than from the other metals, notwithstanding the fact that the corpuscles are more easily absorbed in lead owing to its greater density.

In the case of the soft primary rays, except for silver and nickel, the value of N/N_i is less than the value of N'/N'_i . But the *soft* primary rays are absorbed nearly as much by the other metals as by lead, and therefore the corpuscles will come from as near the surface in one as in the other, and, the density of lead being the greatest, more will get out of the other metals in proportion to the number produced than out of lead. In the case of silver we see that the absorption of the primary rays in lead is again much the greater. Nickel is the only other exception to the above, while zinc, which is more trans-

parent to the primary rays in comparison to lead than nickel is, follows the rule; but a comparison of the absorption coefficients for the corpuscular rays will show that the corpuscles from lead, due to soft primary rays, are nearly as penetrating as those from nickel and much less penetrating than those from zinc. This should easily account for the exception.

Summary.

The results from these experiments may be summarized as follows:—

1. The velocities found from the absorption in aluminium of the corpuscular secondary rays produced when Röntgen rays fall on heavy metals are in good agreement with the velocities found by other investigators, for all the metals considered.

2. The more penetrating primary rays produce more penetrating corpuscular secondary rays.

3. For the more penetrating primary rays used the corpuscular rays from all the metals tested, with the exception of nickel, possessed nearly equal penetrating power; while for the less penetrating primary rays the penetration of the corpuscular rays varied considerably for the different metals, those from lead being the least penetrating.

4. The corpuscular rays produced by hard primary rays are very homogeneous and are absorbed according to an exponential law. Those produced by soft primary rays are not homogeneous, except for tin and silver, but consist of a large number of corpuscles which are absorbed in the first $\cdot 001^{\text{mm}}$ of aluminium, and a smaller number which are not so easily absorbed.

5. In all the metals tested, with one exception, the ratio of the number of corpuscles produced in the metal to the number produced in lead for equal absorptions of the primary rays was greater for metals of greater density. In silver, however, the hard primary rays produced more corpuscles than in lead, which has the *greater* density.

6. The ratio N'/N depends partly on the penetrating power of the corpuscular rays and to a great extent on the ratio of the absorption coefficients of the primary rays in lead and the metal compared with it. Where the primary rays are absorbed to a much greater extent in lead than in the other metal, the corpuscles will be produced much nearer to the surface in lead, and consequently more will escape from the lead, if the corpuscles from the lead are not too much less penetrating than those from the other metal. A good instance of this is silver, where more corpuscles are produced than in lead by the hard primary rays, but yet more get out of the lead than the silver.

If the energy of the corpuscular secondary rays is due, as Prof. J. J. Thomson* has suggested, to an explosion of the atom and not directly to the energy in the primary pulse, it is hard to explain why the more penetrating primary rays give rise to corpuscles of higher velocity than the softer rays do; while the intensity of the primary rays makes no difference in their velocity. The author has been unable to explain this variation in velocity with the nature of the primary pulse, but hopes that further experiments, with modifications in the apparatus, may throw more light on the subject of these corpuscular rays.

It gives me great pleasure to close by expressing my thanks for the valuable advice received from Prof. H. A. Bumstead, at whose suggestion this work was begun.

Sheffield Scientific School of Yale University,
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* Conduction of Electricity through Gases, 2d ed. p. 320.