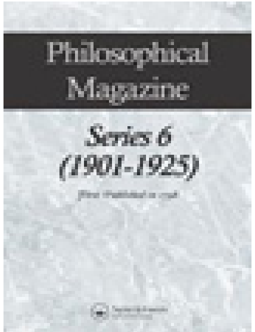

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LVIII. *On the Specific Ionization produced by the Corpuscles given out by Radium.* *By* J. J. E. Durack, 1851 *Exhibition Scholar, Trinity College, Cambridge**.

IN a former paper† I have shown that the corpuscles in the Lenard-ray stream make on the average 0·4‡ positive and negative ions in travelling through one cm. of air at a pressure of one mm. of Hg, or, if we suppose that a corpuscle creates a pair of ions at each collision with the molecules, these corpuscles make 0·4 collision under the conditions of distance and pressure specified above; this number measures what we may call the specific ionization produced by the corpuscles and will be denoted in what follows by the symbol α; it must be noted that we are dealing only with the ionization produced in air, α of course depends on the gas ionized.

Prof. Townsend § has shown that for the corpuscles ‖ produced in air by Röntgen rays the number of ionizing collisions reaches a constant maximum value (equal to 20¶) when the velocity of the corpuscle exceeds a certain amount (about 10^8 cms. per sec.).

I have tried to show ** that the very large difference in the values of α obtained by Townsend and myself can be accounted for by the difference in the velocities of the corpuscles in the two cases, the velocity of the Lenard rays in my experiments being about $4\ 10^9$ cms. per sec.

If the difference be due to the difference in velocity, then, according to the theory indicated, α must decrease as the speed of the corpuscle increases, provided the corpuscle has sufficient energy to produce ions at all the velocities considered.

Now the velocity of the corpuscles given out by by radium (usually called the deflectable Becquerel rays) has been

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

† Phil. Mag. ser. 6, vol. iv.

‡ Starke & Austin (Drude's *Annalen*, Band ix.) have recently shown that 25 per cent. of the corpuscles in the cathode-rays are reflected on striking the surface of an aluminium plate at perpendicular incidence, this introduces an uncertainty in the value 0·4 given above, as it is not certain what becomes of the corpuscles after reflexion, they being under the influence of an electric field. If, in my former experiments, they return to the plate kept at constant potential without producing further ionization the number 0·4 will have to be reduced in the ratio of 4 to 3, *i. e.* to 0·3; at present 0·4 must be regarded as the probable upper limit of the quantity denoted by α.

§ Phil. Mag. ser. 6, vol. i.

‖ See a paper by the same author in 'Nature,' vol. lxv. p. 413.

¶ Further experiments have shown this number to be from 10 to 20 per cent. too large. Townsend, Phil. Mag. ser. 6, vol. iii.

** Phil. Mag. *loc. cit.*

measured by Kaufmann with great accuracy* and found to have all values between $2{\cdot}36\ 10^{10}$ and $2{\cdot}83\ 10^{10}$, so that we should expect α for the deflectable Becquerel rays to be less than that for Lenard rays if the explanation offered be correct.

Townsend states in the paper first mentioned that an estimate of α for radium corpuscles was made by him and found to be at least 13 †, a number considerably greater than 0·4.

In the experiments I am about to describe it will be shown that the number 13 obtained by Townsend is about 76 times too large.

The radioactive substance used in my experiments was radium chloride obtained from the Société Centrale de produits chimiques and labelled initial activity 1000.

The radium ‡ was in the first experiments placed inside a closed vessel and covered with an aluminium plate, the leak being measured between this plate and another above it; the space surrounding the radium was in connexion with the space between the plates through a small hole in order to equalize the air-pressure in the two spaces.

With this apparatus the results of the experiments were difficult to interpret owing to apparatus inside becoming radioactive under the action of the "emanation" from the radium.

The radium was then taken outside and placed about 20 cms. away from the leaking system, so that the emanation could not penetrate to the leaking plates, and also it was certain that a magnetic field in the region in which the radium was placed would not appreciably affect the current between the plates directly.

It was found that in this position practically all the leak was due to deflectable Becquerel rays or the corpuscles from radium; the leak due to the corpuscles alone was, however, too small to be measured accurately, and the radium had to be moved closer to the leaking system.

The final arrangement is shown in fig. 1. One gram of radium was strewn uniformly over the bottom of a lead box B, the top of the box was covered with a thin aluminium leaf l 0·0043 mm. thick in two sets of observations, and with an aluminium plate 0·083 mm. thick in a third.

Above the radium a thick lead plate PP had a hole 2·5 cms. in diameter drilled in the centre, this was covered on top

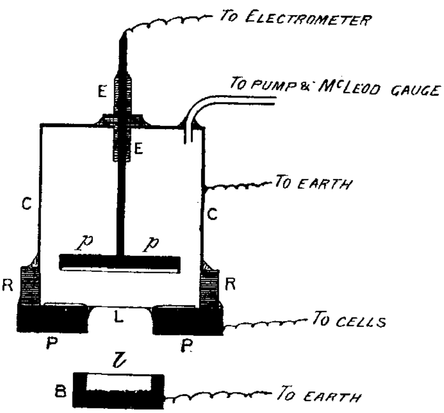
* *Nachrichten d. K. Gesell. d. Wissen. Gottingen*, 1901.

† In these experiments his electrometer was not sufficiently sensitive to measure the leak due to the corpuscles themselves, so that a lower limit only could be found.

‡ This substance is generally spoken of as radium, though it is really mostly radium chloride.

with a plate of aluminium L 0·083 mm. thick, and made air-tight by screwing down a thicker plate of aluminium over it

Fig. 1.



and melting an elastic glue into the crevices. A ring of ebonite RR separated the brass box CC from the lead plate. Above the plate L and 13·5 mm. from it was placed another plate *pp*; the back of this plate was of lead, which was turned so as to form a thin rim of lead on the side nearer L; an aluminium plate similar to L was then placed over the rim and fastened to it so that there was an air-space between the aluminium and the lead ; *pp* was connected to a quadrant electrometer with a rod passing through the ebonite plug E and shielded from electrostatic effects.

The space inside CC was in communication with a pump and McLeod gauge.

All joints between metal and ebonite and between metal and glass were made air-tight with sealing-wax.

The plate PP was 8 cms. diameter, and the apparatus is drawn to scale in fig. 1.

During the time the observations were being made CC and B were kept connected to earth, and PP to one pole of a battery of storage-cells, the other pole being to earth. By keeping B connected to earth while P is charged to a high potential the ions formed in the air between B and P are destroyed, and consequently prevented from diffusing out and, may be, finding their way to the electrometer.

It is known from the experiments of Rutherford * that an aluminium plate 0·08 mm. thick is sufficient to absorb all the

* See Rutherford and Miss Brooks, Phil. Mag. ser. 6, vol. iv. p. 5.

so-called "α" or non-deflectable rays, and hence the conductivity produced in the gas between PP and *pp* was due to the deflectable rays; this was verified by preliminary experiments on the action of a magnetic field on the rate of leak.

It has been shown by many experimenters that a metal plate struck by Röntgen or cathode-rays gives out negatively charged ions; moreover, that the rate at which these ions are given out is greater for the heavy metals than for the light ones, this effect is very small when Röntgen rays fall on an aluminium plate.

For this reason the plate *pp* has been made as described above; there will be very little absorption of the Becquerel rays by the aluminium plate on the face of *pp*, and consequently very little tendency to give out negative ions, practically all the absorption takes place in the lead, but this will not cause any error in the measured leak due to the corpuscles themselves unless these ions are given out with sufficient velocity to carry them back through the aluminium plate; from the experiments of Sagnac on the secondary ionization produced at the surface of a metal by Röntgen rays it is probable that they would not have sufficient velocity to do this.

The opposite surfaces of PP and *pp* being both of the same metal, there should be no error due to a contact P.D. effect.

The electrometer used in these experiments was of the Dolezalek type, the insulation of the quadrants being greatly improved and a gilt mica needle used instead of the paper needle of Dolezalek. The needle was kept charged to a constant potential by dipping the suspending quartz fibre into a solution of $CaCl_2$ and connecting the needle through the fibre to a battery *.

The ordinary formula for the sensibility of a quadrant electrometer, *the needle being kept at constant potential* V_3, is

$$\theta = \frac{1}{\tau}\frac{dq_{11}}{d\theta}(V_1 - V_2)(V_3 - \tfrac{1}{2}\overline{V_1 + V_2})$$

where θ is the deflexion produced by a P.D. $(V_1 - V_2)$ between the two pairs of quadrants, τ is the torsion of the suspending fibre per unit angular displacement, and q_{11} is the coefficient of capacity of a pair of quadrants, all other conductors in the neighbourhood being kept at zero potential.

* Dolezalek, *Zeits. für Instrument.* Dec. 1901.

If V_2 be kept constantly $=0$, and V_1 be small in comparison with V_3, this formula takes the usual form

$$\theta = \frac{1}{\tau}\frac{dq_{11}}{d\theta}V_1V_3.$$

Now it has been shown by Hopkinson* that the apparent capacity of a pair of quadrants (say the pair 1) when the needle is charged to a potential V_3 is equal to

$$q_{11} + \overline{\frac{dq_{11}}{d\theta}}\Big|^2 \frac{1}{\tau} V_3^2. \quad . \quad . \quad . \quad . \quad . \quad . \quad (A)$$

Suppose a quantity of electricity Q_1 given to the pair of quadrants 1, the potential V_1 will be

$$V_1 = Q_1/q_{11} + \left(\frac{dq_{11}}{d\theta}\right)^2 \frac{1}{\tau} V_3^2,$$

and for the formula A we may write

$$\theta/Q_1 = \frac{1}{\tau}\frac{dq_{11}}{d\theta}V_3/q_{11} + \left(\frac{dq_{11}}{d\theta}\right)^2 \frac{1}{\tau} V_3^2.$$

Hence θ/Q_1 (which is the sensibility for current) has a maximum value for a certain value of V_3, viz.:—

$$V_3 = \sqrt{q_{11}\tau}\left(\frac{dq_{11}}{d\theta}\right).$$

When high sensibility for leaks is an important factor the needle should be charged to this potential, and even when high sensibility is not required it is advisable to work with the electrometer at its maximum sensibility, for then small changes in V_3 make no change in θ/Q_1.

The value of V_3 for which θ/Q_1 is a maximum is easily found by measuring the capacity of a pair of quadrants and finding for what value of V_3 this capacity is equal to $2q_{11}$, *i. e.*, twice the capacity when $V_3=0$. With my electrometer this was the case when V_3 was equal to 60 volts. The observations from which α was to be deduced were made as follows:—The plate PP was connected to one pole of a battery of cells (say the positive pole), the other pole being to earth, a small P.D. was set up initially between the two pairs of quadrants, the insulated pair being initially negative with respect to the earthed pair if the leak to be measured was positive, and positive if the leak was negative; thus the needle travelled through its zero position in taking a reading, which was done by finding the time required for the light-spot to pass over a certain number of divisions on the scale, these divisions being half on one side and half on the other side of the zero.

By reading in this way the effect of changes in capacity

* Phil. Mag. ser. 5, vol. xix.

for different deflexions (which are, however, usually very small) is eliminated, and leaks due to faulty insulation are minimized, these leaks helping the leak to be measured for half the time and opposing it for the other half.

It is of great importance that the P.D. between PP and *pp* should be sufficient to saturate the gas, *i. e.*, to remove the ions as fast as they are formed.

In the first two series of observations the current was measured for several different P.D.'s, and in the third a P.D. was always applied which was known from the previous observations to be sufficient to produce saturation. The nature of the current-E.M.F. curves may be seen from the results given in Table I. and plotted in fig. 2.

Fig. 2.

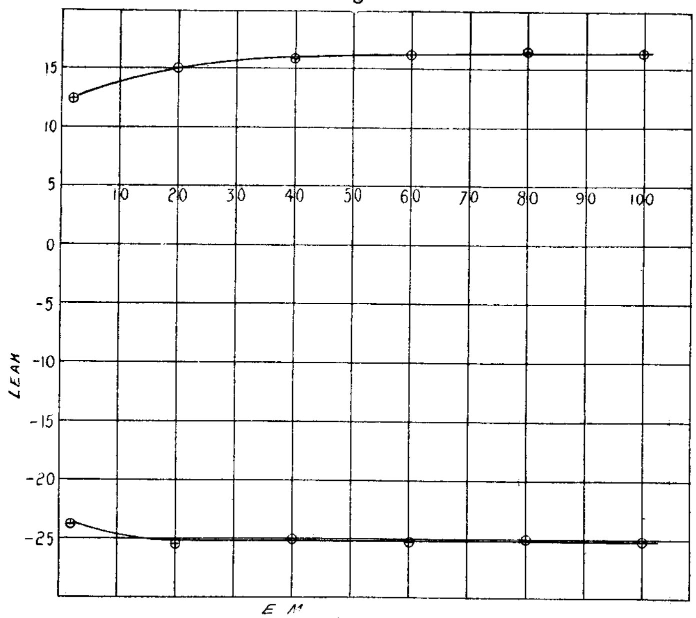


TABLE I.

Pressure.	P. D.	Current.	
		Lower Plate +.	Lower Plate −.
19·0	2	+12·4	−23·8
	20	+15·0	−25·5
	40	+15·8	−25·0
	60	+16·1	−25·2
	80	+16·4	−25·0
	100	+16·3	−25·1

The first column gives the pressure in mm., the second column the average P.D. during the leak between PP and *pp* in volts, the third column the current when PP was connected to the positive pole of the battery, and the fourth the current when the field was reversed.

The positive current is taken in the direction PP to *pp*, so that *pp* receives a positive charge, the unit of current here, as in all the tables and curves, is 10^{-14} amp.

It will be seen from fig. 2 that at a pressure of 19 mm. the gas is practically saturated with a P.D. of 40 volts.

Care must be taken, not only that the E.M.F. is sufficient to saturate the gas, but also that it is not too great, otherwise the negative ions generated by the Becquerel rays may, as has been shown by Townsend (*loc. cit.* Phil. Mag. vol. i.), themselves generate other ions; calculation from Townsend's numbers shows that the effect would begin to be evident in my experiments when $V = 45\,p$, where V is the P.D. in volts and p is the pressure in mm. In all the tables V is less than $45\,p$.

As all the observations could not be carried out in a single day, and the radium had to be kept dry to prevent it from deteriorating in strength, the box B was removed at the end of each day and kept in a drying-apparatus, stops were made for B to fit into so that it could be replaced in the same position on the following day, to make sure that this was so the last readings of the previous day were repeated each morning.

Table II.

Pressure.	P. D.	Current.	
		Lower Plate +.	Lower Plate −.
20·5	60 to 100	+18·4	−28·8
15·7	100	+12·9	−23·0
12·0	,,	+ 8·6	−18·3
9·3	60 to 100	+ 6·0	−14·7
7·3	20 to 100	+ 3·5	−12·7

The first series of observations for the determination of α is given in Table II. and plotted in fig. 3; when these five points were determined the box B was accidentally knocked, and the exposed surface of the radium thereby considerably altered, as was seen afterwards on removing the thin aluminium leaf which covered B when the observations given in Tables II. and III. were taken.

Fig. 3.

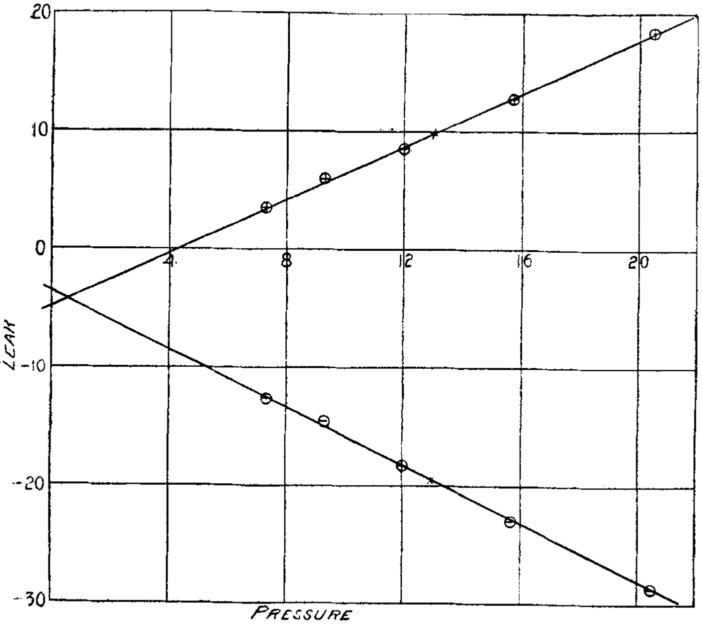


TABLE III.

Pressure.	P. D.	Current.	
		Lower Plate +.	Lower Plate −.
0·68	2 to 20	−2·82	− 4·20
2·52	20 to 40	−1·34	− 5·90
5·26	,,	+1·20	− 8·34
7·9	,,	+3·36	−10·8
10·7	20 to 100	+5·60	−13·5

The numbers given in Table IV. and plotted in fig. 5, were found with an aluminium plate 0·083 mm. thick on the top of B.

The lines in figs. 3, 4, and 5 have all been drawn through the centroid of the points* which is marked with a cross, the

* See Pearson "On the Lines and Planes of Closest Fit," Phil. Mag. ser. 6, vol. ii.

centroid of n points, whose coordinates are x_1, x_2, &c., y_1, y_2, &c., being defined by the coordinates

$$\bar{x} = \frac{\Sigma x}{n},$$

$$\bar{y} = \frac{\Sigma y}{n}.$$

Fig. 4.

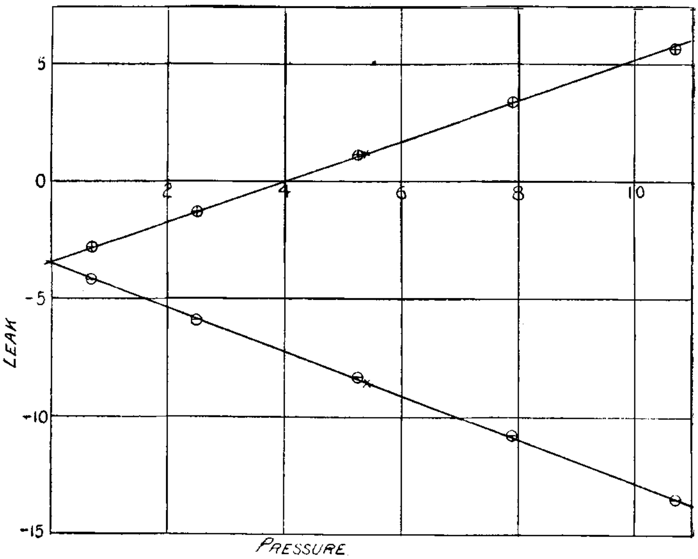


TABLE IV.

Pressure.	P. D.	Current.	
		Lower Plate +.	Lower Plate −.
10·7	60	+5·40	−13·2
7·8	"	+3·03	−10·3
5·6	"	+1·36	− 8·4
4·04	"	+0·09	− 7·2
2·92	20 to 60	−1·15	− 6·0
2·13	"	−1·60	− 5·44
1·51	"	−2·24	− 4·86
1·08	"	−2·80	− 4·58
0·50	2	−3·56	− 4·36
0·015	0	−3·90	− 3·90

Figs. 3, 4, and 5 show that the relation between current and pressure is of the form

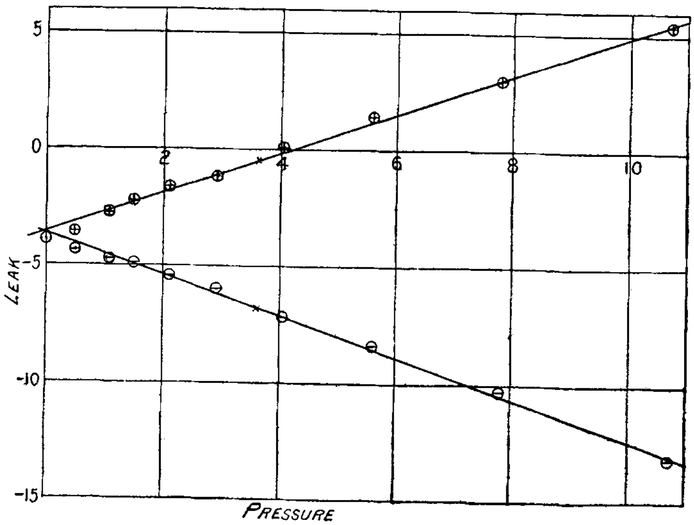
$$\gamma_1 = -c + mp$$

when the lower plate is charged positively, and

$$\gamma_2 = -c - mp$$

when charged negatively, γ_1 and γ_2 denoting the currents, p the pressure, and m and c positive constants.

Fig. 5.



The interpretation of this result is very simple : we have negatively charged corpuscles constituting the deflectable Becquerel rays travelling from PP to *pp* at a rate independent of the pressure, on their way they produce equal numbers of positive and negative ions in the gas, the rate of production being proportional to the pressure.

Let N_0 be the number of corpuscles passing per second through L and e the charge carried by a single corpuscle, then the current due to the corpuscles alone is $-N_0 e$.

Suppose that each corpuscle makes α collisions in traversing one cm. of the gas at a pressure of one mm., let p be the pressure, d the average distance travelled by the corpuscles in going from PP to *pp*, and e' the charge carried by the ions generated in the gas.

When the lower plate is charged positively *pp* will collect positive ions from the gas, and the total current will be

$$\gamma_1 = -N_0 e + N_0 e' \alpha p d.$$

When the field is reversed *pp* will collect negative ions from the gas, and the current will be

$$\gamma_2 = -N_0 e - N_0 e' \alpha p d.$$

It has been shown by many experimenters that e/m, the ratio of the charge to the mass, is approximately the same for cathode-rays, Becquerel rays, the ions producing the Zeeman effect, and the ions given off by Zn under the action of ultra-violet light, and 1000 times greater than that for the H ion in electrolysis. It has also been shown by J. J. Thomson * (by direct measurement of both) that the charge carried by the ions given out by Zn is the same as the charge on the ions produced in air by Röntgen rays. Townsend † has proved, by direct comparison, that the charges on the ions produced in air by Röntgen rays, Becquerel rays, and point discharges, and on the ions given off by Zn are all equal to the charge carried by the H ion in electrolysis.

The same experimenter has shown ('Nature,' *loc. cit.*) that the ions produced in air are identical as regards mass and charge with the ions given off by Zn under the action of ultra-violet light.

From these facts Prof. Thomson has concluded that in all these cases the charges carried by the negative ions are all equal, and the mass of the carrier about 1000 times smaller than the H atom. Hence in the equations 1 and 2 we may put $e = e'$ and we have

$$\gamma_1 = -N_0 e(1 - \alpha p d) \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\gamma_2 = -N_0 e(1 + \alpha p d) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

From which we obtain

$$-N_0 e = \tfrac{1}{2}(\gamma_1 + \gamma_2)$$

and

$$\alpha = \frac{1}{pd}\left(\frac{\gamma_2 - \gamma_1}{\gamma_1 + \gamma_2}\right).$$

To find the average distance travelled by the corpuscles between PP and *pp* we know from Becquerel's experiments on the velocity of the deflectable Becquerel rays, that the corpuscles are projected in all directions from the surface of the radium, hence in these experiments d will lie between 13·5 mm. (the perpendicular distance between the plates) and 14·3 mm. and cannot be far from 14 mm.

* Phil. Mag. Dec. 1899.

† Phil. Trans. 1899, 1900.

The average values of N_0e and of α for all the observations in any series of experiments are found directly from figs. 3, 4, and 5, being the values deduced from the position of the centroid in the three cases.

The centroids are given by

III.	IV.	V.
$\bar{p} = 13{\cdot}0$	$\bar{p} = 5{\cdot}42$	$\bar{p} = 3{\cdot}63$
$\bar{\gamma}_1 = +9{\cdot}88$	$\bar{\gamma}_1 = +1{\cdot}2$	$\bar{\gamma}_1 = -0{\cdot}54$
$\bar{\gamma}_2 = -19{\cdot}5$	$\bar{\gamma}_2 = -8{\cdot}55$	$\bar{\gamma}_2 = -6{\cdot}8$

Hence we find

$$N_0e = 4{\cdot}8 \text{ III.} \qquad \text{and} \qquad \alpha = {\cdot}168 \text{ III.}$$
$$= 3{\cdot}7 \text{ IV.} \qquad\qquad = {\cdot}175 \text{ IV.}$$
$$= 3{\cdot}7 \text{ V.} \qquad\qquad = {\cdot}168 \text{ V.}$$

The values of N_0e obtained show that the effect of putting an aluminium plate over B (and practically doubling the distance travelled by the corpuscles before they reach the place where the ionization was measured) was to reduce the Becquerel ray current in the ratio of 4·8 to 3·7.

The tilting of the radium also reduced this current as we should expect, for the surface exposed was thereby decreased. This accounts for N_0e being less in fig. 4 than in fig. 3.

The effect on α is hardly appreciable, for the difference only amounts to about 4 per cent. which is inside the limit of possible error.

From the values of α given above it may been that the mean free path of the Becquerel ray corpuscles in air at 1 mm. is about 6 cms. This very large value for the mean free path accounts for the very small absorption of the deflectable Becquerel rays.

In conclusion, my thanks are due to Prof. J. J. Thomson for many suggestions given during the progress of the work.

Cavendish Laboratory, Cambridge.

LIX. *Condensation of the Radioactive Emanations.* By E. Rutherford, *M.A., D.Sc., Macdonald Professor of Physics, McGill University, Montreal, and* F. Soddy, *M.A. (Oxon.)*.

[Plate XIV.]

IN a previous paper (Phil. Mag. 1902, iv. p. 581) we have shown that the radioactive emanation from thorium passes in unchanged amount through a white-hot platinum tube and through a tube cooled to the temperature of solid carbon

* Communicated by the Authors.