E. Rutherford, Philos. Mag. **47,** 109 **1899**

Uranium Radiation and the Electrical conduction Produced by it

E. Rutherford,
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The remarkable radiation emitted by uranium and its compounds has been studied by its discoverer, Becquerel, and the results of his investigations on the nature and properties of the radiation have been given in a series of papers in the Comptes Rendus[1]. He showed that the radiation, continuously emitted from uranium compounds, has the power of passing through considerable thicknesses of metals and other opaque substances; it has the power of acting on a photographic plate and of discharging positive and negative electrification to an equal degree. The gas through which the radiation passes is made a temporary conductor of electricity and preserves its power of discharging electrification for a short time after the source of radiation has been removed. The results of Becquerel showed that Röntgen and uranium radiations were very similar in their power of penetrating solid bodies and producing conduction in a gas exposed to them; but there was an essential difference between the two types of radiation. He found that uranium radiation could be refracted and polarized, while no definite results showing polarization or refraction have been obtained for Röntgen radiation.

It is the object of the present paper to investigate in more detail the nature of uranium radiation and the electrical conduction produced. As most of the results obtained have been interpreted on the ionization–theory of gases which was introduced to explain the electrical conduction produced by Röntgen radiation, a brief account is given of the theory and the results to which it. leads.

In the course of the investigation, the following subjects have been considered:–

§ 1. Comparison of methods of investigation.

[1] C.R. 1896, pp. 420, 501, 559, 689, 762, 1086; 1897, pp. 438, 800

§ 1 *Comparison of Methods of Investigation.*

The properties of uranium radiation may be investigated by two methods, one depending on the action on a photographic plate and the other on the discharge of electrification. The photographic method is very slow and tedious, and admits of only the roughest measurements. Two or three days' exposure to the radiation is generally required to produce any marked effect on the photographic plate. In addition, when we are dealing with very slight photographic action, the fogging of the plate, daring the long exposures required, by the vapours of substances[2] is liable to obscure the results. On the other hand the method of testing the electrical discharge caused by the radiation is much more rapid than the photographic method, and also admits of fairly accurate quantitative determinations.

The question of polarization and refraction of the radiation can, however, only be tested by the photographic method. The electrical experiment (explained in § 2) to test refraction is not very satisfactory.

§ 2 *Polarization and Refraction.*

The almost identical effects produced in gases by uranium and Röntgen radiation (which will be described later) led me to consider the question whether the two types of radiation did not behave the same in other respects.

In order to test this, experiments were tried to see if uranium radiation could be polarized or refracted. Becquerel[3] had found evidence of polarization and refraction, but in repeating experiments similar to those tried by him, I have been unable to find any evidence of either. A large number of photographs by the radiation have been taken under various conditions, but in no case have I been able to observe any effect on the photographic plate which showed the presence of polarization or refraction.

In order to avoid fogging of the plate during the long exposures required, by the vapours of substances, lead was employed as far as possible in the neighbourhood of the plate, as its effect on the film is very slight.

A brief account will now be given of the experiments on refraction and polarization.

Refraction. — A thick lead plate was taken and a long narrow slit

[2]Russell, Proc. Roy. Soc. 1897.
[3]C.R. 1896, p. 559

cut through it; this was placed over a uniform layer of uranium oxide; the arrangement was then equivalent to a line source of radiation and a slit. Thin prisms of glass, aluminium, and paraffin–wax were fixed at intervals on the lead plate with their edges just covering the slit, A photographic plate was supported 5 mms. from the slit. The plate was left for a week in a dark box. On developing a dark line was observed on the plate. This line was not appreciably broadened or displaced above the prisms. Different sizes of slits gave equally negative results. If there was any appreciable retraction we should expect the image of the slit to be displaced from the line of the slit.

Becquerel[4] examined the opacity of glass for uranium radiation in the solid and also in a finely–powdered state by the method of electric leakage, and found that, if anything, the transparency of the glass for the radiation was greater in the finely–divided than in the solid state. I have repeated this experiment and obtained the same result. As Becquerel stated, it is difficult to reconcile this result with the presence of refraction.

Polarization. — An arrangement very similar to that used by Becquerel was employed. A deep hole was cut in a thick lead plate and partly filled with uranium oxide. A small tourmaline covered the opening. Another small tourmaline was cut in two and placed on top of the first, so that in one half of the opening the tourmalines were crossed and in the other half uncrossed. The tourmalines were very good optically. The photographic plate was supported 1 to 3 mm. above the tourmalines. The plate was exposed four days, and on developing a black circle showed up on the plate, but in not one of the photographs could the slightest difference in the intensity be observed. Becquerel[5] stated that in his experiment the two halves were unequally darkened, and concluded from this result that the radiation was doubly refracted by tourmaline, and that the two rays were unequally absorbed.

§ 3 *Theory of Ionization.*

To explain the conductivity of a gas exposed to Röntgen radiation, the theory[6] has been put forward that the rays in passing through the gas produce positively and negatively charged particles in the gas, and that the number produced per second depends on the intensity of the radiation and

[4] C.R. 1886, p. 559.
[5] C.R. 1886, p. 559.
[6] J.J. Thomson and E. Rutherford, Phil. Mag .M Nov. 1896.

the pressure.

These carriers are assumed to be so small that they will move with a uniform velocity through a gas under a constant potential gradient. The term ion was given to them from analogy with electrolytic conduction, but in using the term it is not assumed that the ion is necessarily of atomic dimensions; it may be a multiple or submultiple of the atom.

Suppose we have a gas between two plates exposed to the radiation and that the plates are kept at a constant difference of potential. A certain number of ions will be produced per second by the radiation and the number produced will in general depend on the pressure of the gas. Under the electric field the positive ions travel towards the negative plate and tho negative ions towards the other plate, and consequently a current will pass through the gas. Some of the ions will also recombine, the rate of recombination being proportional to the square of the number present. The current passing through the gas for a given intensity of radiation will depend on the difference of potential between the plates, but when the potential–difference is greater than a certain value the current will reach a maximum. When this is the case all the ions are removed by the electric field before they can recombine.

The positive and negative ions will be partially separated by the electric field, and an excess of ions of one sign may be blown away, so that a charged gas will be obtained. If the ions are not uniformly distributed between the plates, the potential gradient will be disturbed by the movement of the ions.

If energy is absorbed in producing ion, we should expect the absorption to be proportional to the number of ions produced and thus depend on the pressure. If this theory be applied to uranium radiation we should expect to obtain the following results: —

(1) Charged carriers produced through the volume of the gas.

(2) Ionization proportional to the intensity of the radiation and the pressure.

(3) Absorption of radiation proportional to pressure.

(4) Existence of saturation current.

(5) Rate of recombination of the ions proportional to the square of the number present.

(6) Partial separation of positive and negative ions.

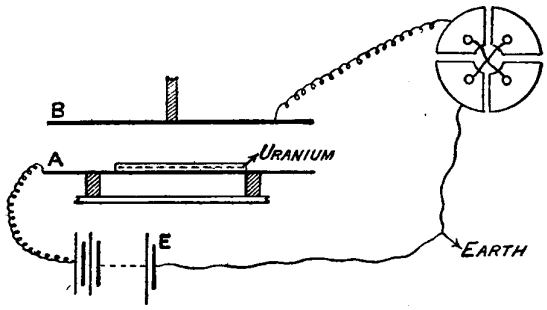

Figure 1:

(7) Disturbance of potential gradient under certain conditions between two plates exposed to the radiation.

The experiments now to be described sufficiently indicate that the theory does form a satisfactory explanation of the electrical conductivity produced by uranium radiation.

In all experiments to follow, the results are independent of the sign of the charged plate, unless the contrary is expressly stated.

§ 4 *Complex Nature of Uranium Radiation.*

Before entering on the general phenomena of the conduction produced by uranium radiation, an account will be given of some experiments to decide whether the same radiation is emitted by uranium and its compounds and whether the radiation is homogeneous. Röntgen and others have observed that the x–rays are in general of a complex nature, including rays of wide differences in their power of penetrating solid bodies. The penetrating power is also dependent to a large extent on the stage of exhaustion of the Crookes tube.

In order to test the complexity of the radiation, an electrical method was employed. The general arrangement is shown in fig. 1.

The metallic uranium or compound of uranium to be employed was powdered and spread uniformly over the centre of a horizontal zinc plate A, 20 cm. square. A zinc plate B, 20 cm. square, was fixed parallel to A and 4 cm. from it. Both plates were insulated. A was connected to one pole of a battery of 50 volts, the other pole of which was to earth; B was

connected to one pair of quadrants of an electrometer, the other pair of which was connected to earth.

Under the influence of the uranium radiation there was a rate of leak between the two plates A and B. The rate of movement of the electrometer–needle, when the motion was steady, was taken as a measure of the current through the gas.

Successive layers of thin metal foil were then placed over the uranium compound and the rate of leak determined tor each additional sheet. The table (p. 115) shows the results obtained for thin Dutch metal.

In the third column the ratio of the rates of leak for each additional thickness of metal leaf is given. Where two thicknesses were added at once, the square root of the observed ratio is taken, for three thicknesses the cube root. The table shows that for the first ten thicknesses of metal the rate of leak diminished approximately in a geometrical progression as the thickness of the metal increased in arithmetical progression.

Thickness of Metal Leaf 0.00008 cm.
Layer of Uranium Oxide on plate.

Number of Layers	Leak per min. in scale–divisions	Ratio for each layer
0	91	
1	77	0.85
2	60	0.78
3	49	0.82
4	42	0.86
5	33	0.79
6	24.7	0.75
8	15.4	0.79
10	9.1	0.77
13	5.8	0.86

It will be shown later (§ 8) he rate of leak between two plates for a saturating voltage is proportional to the intensity of the radiation after passing through the metal. The voltage of 50 employed was not sufficient to saturate

the gas, but it was found that the comparative rates of leak under similar conditions for 50 and 200 volts between the plates were nearly the same. When we are dealing with very small rates of leak, it is advisable to employ as small a voltage as possible, in order that any small changes in the voltage of the battery should not appreciably affect the result. For this reason the voltage of 50 was used, and the comparative rates of leak obtained are very approximately the same as for saturating electromotive force.

Since the rate of leak diminishes in a geometrical progression with the thickness of metal, we see from the above statement that the intensity of the radiation falls off in a geometrical progression, i.e. according to an ordinary absorption law. This shows that the part of the radiation considered is approximately homogeneous.

With increase of the number of layers the absorption commences to diminish. This is shown more clearly by using uranium oxide with layers of thin aluminium leaf (see table p. ????116).

It will be observed that for the first three layers of aluminium foil, the intensity of the radiation falls off according to the ordinary absorption law, and that, after the fourth thickness, the intensity of the radiation is only slightly diminished by adding another eight layers.

Thickness of Aluminium foil 0.0005 cm.

Number of Layers Of Aluminium foil	Leak per min. in scale–divisions	Ratio
0	182	
1	77	0.42
2	33	0.43
3	14.6	0.44
4	9.4	0.65
12	7	

The aluminium foil in this case was about 0.0005 cm. thick, so that after the passage of the radiation through 0.002 cm. of aluminium the intensity of the radiation is reduced to about $^1/_{20}$ of its value. The addition of a thickness of 0.001 cm. of aluminium has only a small effect in cutting down the rate of leak. The intensity is, however, again reduced to about half of

its value after passing through an additional thickness of 0.05 cm., which corresponds to 100 sheets of aluminium foil.

These experiments show that the uranium radiation is complex, and that there are present at least two distinct types of radiation one that is very readily absorbed, which will be termed for convenience the radiation, and the other of a more penetrative character, which will be termed the β radiation.

The character of the β radiation seems to be independent of the nature of the filter through which it has passed. It was found that radiation of the same intensity and of the same penetrative power was obtained by cutting off the α radiation by thin sheets of aluminium, tinfoil, or paper. The β radiation passes through all the substances tried with far greater facility than the a radiation. For example, a plate of thin cover–glass placed over the uranium reduced the rate of leak to $^{1}/_{30}$ of its value; the β radiation, however, passed through it with hardly any loss of intensity.

Some experiments with different thicknesses of aluminium seem to show, as far as the results go, that the β radiation is of an approximately homogeneous character. The following table gives some of the results obtained for the β radiation from uranium oxide:—

β Radiation

Thickness of	Rate of Leak
0.005	1
0.028	0.68
0.51	0.48
0.09	0.25

The rate of leak is taken as unity after the α radiation has been absorbed by passing through ten layers of aluminium foil. The intensity of the radiation diminishes with the thickness of metal traversed according to the ordinary absorption law. It must be remembered that when we are dealing with the β radiation alone, the rate of leak is in general only a few per cent. of the leak due to the α radiation, so that the investigation of the homogeneity of the β radiation cannot, be carried out with the same accuracy as for the radiation. As far, however, as the experiments have gone the results

seem to point to the conclusion that the β radiation is approximately homogeneous, although it is possible that other types of radiation of either small intensity or very great penetrating power may be present.

§ 5 *Radiation Emitted by Different Compounds of Uranium.*

All the compounds of uranium examined gave out the two types of radiation, and the penetrating power of the radiation for both the α and β radiations is the same for all the compounds. The table (???p. 118) shows the results obtained for some of the uranium compounds.

Fig. 2 shows graphically some of the results obtained for the various uranium compounds. The ordinates represent rates of leak, and the abscissæthicknesses of aluminium through which the radiation has passed.

The different compounds of uranium gave different rates of leak, but, for convenience of comparison, the rate of leak due to the uncovered salt is taken as unity.

It will be seen that the rate of decrease is approximately the same for the first layer of metal, and that the rate of decrease becomes much slower after four thicknesses of foil.

The rate of leak due to the β radiation is a different proportion of the total amount in each case. The uranium

Thickness of aluminium foil 0.0005 cm.

Number of Layers of Aluminium foil	Proportionate Rate of Leak			
	Uranium metal	Uranium Nitrate	Uranium Oxide	Uranium Potassium Sulphate
0	1	1	1	1
1	0.51	0.43	0.42	0.42
2	0.35	0.28	0.18	0.27
3	...	0.17	0.08	0.17
4	...	0.15	0.05	0.12
5	0.15	...	...	...
12	...	0.125	0.04	0.11

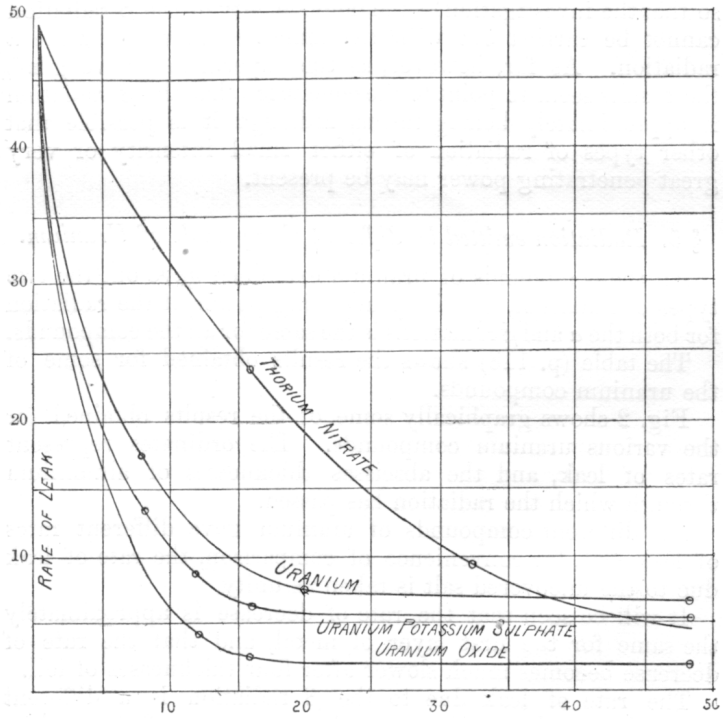

Figure 2: Thickness of aluminium: each division 0.00012 cm.

metal was used in the form of powder, and a smaller area of it was used than in the other cases. For the experiments on uranium oxide a thin layer of fine powder was employed, and we see, in that case, that the β radiation bears a much smaller proportion to the total than for the other compounds. When a thick layer of the oxide was used there was, however. an increase in the ratio, as the following table shows: —

Number oflayers of Aluminium foil	Rate of Leak	
	Thin layer of UraniumOxide	Thick layer of Uranium Oxide
0	1	1
1	0.42	5
2	0.18	...
4	0.05	0.12
8	...	0.113
12	0.04	...
18	...	0.11

The amount of the α radiation depends chiefly on the surface of the uranium compound, while the β radiation depends also on the thickness of the layer. The increase of the rate of leak due to the β radiation with the thickness of the layer indicates that the β radiation can pass through a considerable thickness of the uranium compound. Experiments showed that the leak due to the a radiation did not increase much with the thickness of the layer. I did not, however, have enough uranium salt to test the variation of the rate of leak due to the β radiation for thick layers.

The rate of leak from a given weight of uranium or uranium compound depends largely on the amount of surface. The greater the surface, the greater the rate of leak. A small crystal of uranium nitrate was dissolved in water, and the water then evaporated so as to deposit a thin layer of the salt over the bottom of the dish. This gave quite a large leakage. The leakage in such a case is due chiefly to the α radiation.

Since the rate of leak due to any uranium compound depends largely on its amount of surface, it is difficult to compare the quantity of radiation given out by equal amounts of different salts: for the result will depend greatly on the state of division of the compound. It is possible that the apparently very powerful radiation obtained from pitchblende by Curie[7] may be partly due to the very fine state of division of the substance rather than to the presence of a new and powerful radiating substance.

The rate of leak due to the β radiation is, as a rule, small compared with that produced by the α radiation. It is difficult, however, to compare the relative intensities of the two kinds. The α radiation is strongly absorbed

[7] C.R July 1898, p.175.

by gases (§ 8), while the β radiation is only slightly so. It will be shown later (§ 8) that the absorption of the radiation by the gas is approximately proportional to the number of sons produced. If therefore the β radiation is only slightly absorbed by the gas, the number of ions produced by it is small, i.e. the rate of leak is small. The comparative rates of leak due to the α, and β radiation is thus dependent on the relative absorption of the radiations by the gas as well as on the relative intensity.

The photographic actions of the α and β radiations have also been compared. A thin uniform layer of uranium oxide was sprinkled over a glass plate; one half of the plate was covered by a piece of aluminium of sufficient thickness to practically absorb the α radiation. The photographic plate was fixed about 4 mm. from the uranium surface. The plate was exposed 48 hours, and, on developing, it was found that the darkening of the two halves was not greatly different. On the one half of the plate the action was due to the β radiation alone, and on the other due to the α and β radiations together. Except when the photographic plate is close to the uranium surface, the photographic action is due principally to the β radiation.

§ 6 *Transparency of Substance to the two Types of Radiation.*

If the intensity of the radiation in traversing a substance diminishes according to the ordinary absorption law, the ratio τ of the intensity of the radiation after pacing through a distance d of the substance to the intensity when the substance is removed is given by

$$\tau = e^{-\lambda d},$$

where λ is the coefficient of absorption and $e = 2.7$.

In the following table a few values of λ are given for the α and β radiations, assuming in each case that the radiation is simple and that the intensity falls off according to the above law:—

Substance	λ for the α radiation	λ for the β radiation
Dutch metal	2700	...
Aluminium	1600	15
Tinfoil	2650	108
Copper	...	49
Silver	...	97
Platinum	...	240
Glass	...	5.6

The above results show what a great difference there is in the power of penetration of the two types of radiation. The transparency of aluminium for the β radiation is over 100 times as great as for the α radiation. The opacity of the metals aluminium, copper, silver, platinum for the β radiation follows the same order as their atomic weights. Aluminium is the most transparent of the metals used, but glass is more transparent than aluminium for the β radiation. Platinum has an opacity 16 times as great as aluminium. For the α radiation, aluminium is more transparent than Dutch metal or tinfoil.

For a thickness of aluminium 0.09 cm. the intensity of the β radiation was reduced to 0.26 of its value; for a thickness of copper 0.03 cm. the intensity was reduced to 0.23 of its value. These results are not in agreement with some given by Becquerel[8] who found copper was more transparent than aluminium for uranium radiation.

The β radiation has a penetrating power of about the same order as the radiation given out by an average x–ray bulb, Its power of penetration is, however, much less than for the rays from a "hard" bulb. The α radiation, on the other hand, is far more easily absorbed than rays from an ordinary bulb, hut is very similar in its penetrating power to the secondary radiation[9] sent out when x–rays fall upon a metal surface.

It is possible that the α radiation is a secondary radiation set up at the surface of the uranium by the passage of the β radiation through the uranium, in exactly the same way as a diffuse radiation is produced at the

[8] C.R. 1896, p. 763.

[9] Perrin, C.R. CXXIV. p. 455; Sagnac, C.R. 1898.

surface of a metal by the passage of Röntgen–rays through it. There is not, however, sufficient evidence at present to decide the question.

§ 7 *Thorium Radiation.*

While the experiments on the complex nature of uranium radiation were in progress, the discovery[10] that thorium and its salts also emitted a radiation, which had general properties similar to uranium radiation, was announced. A few experiments were made to compare the types of radiation emitted by uranium and thorium.

The nitrate and the sulphate of thorium were used and gave similar results, although the nitrate appeared to be the more active of the two. The leakage effects due to these salts were of quite the same order as those obtained for the uranium compounds; but no satisfactory quantitative comparison can be made between the uranium and thorium salts as the amount of leak depends on the amount of surface and thickness of the layer.

It was found that thorium nitrate when first exposed to the air on a platinum plate was not a steady source of radiation, and for a time the rate of leak varied very capriciously, being sometimes five times as great as at others. The salt was very deliquescent, but after exposure of some hours to the atmosphere the rate of leak became more constant and allowed of rough comparative measurements. Thorium sulphate was more constant than the nitrate.

The absorption of the thorium radiation was tested in the same way as for uranium radiation. The following table gives some of the results. The aluminium foil was of the same thickness (0.0005cm.) a s that used in the uranium experiment: —

[10] G.C. Schmidt, Wied.*Annal.* May 1898.

Number of Layers of Aluminium foil	Leak per minute in scale–divisions
0	200
4	94
8	37
12	19
17	7.5

The curve showing the relation between the rate of leak and the thickness of the metal traversed is shown in fig. 2 (p. 118????), together with the results for uranium. It will be seen that thorium radiation is different in penetrative power from the α radiation of uranium. The radiation will pass through between three and four thicknesses of aluminium foil before the intensity is reduced to one–half, while with uranium radiation the intensity is reduced to less than a half after passing through one thickness of foil.

With a thick layer of thorium nitrate it was found that the radiation was not homogeneous, but rays of a more penetrative kind were present. On account of the inconstancy of thorium nitrate as a source of radiation, no accurate experiments have been made on this point.

The radiations from thorium and uranium are thus both complex, and as regards the α type of radiation are different in penetrating power from each other.

In all the experiments on uranium and thorium, care was taken that no stray radiation was present which would obscure the results. Such precautions are very necessary when the rate of leak, due to the radiation transmitted through a considerable thickness of metal, is only a small percentage of the total. The method generally employed was to cover the layer of active salt with the metal screen, and then place in position over it a large sheet of lead with a rectangular hole cut in it of smaller area than that of the layer of salt. The lead was pressed tightly down, and the only radiation between the parallel plates had to pass through the metal screen, as the lead was too thick to allow any to go through.

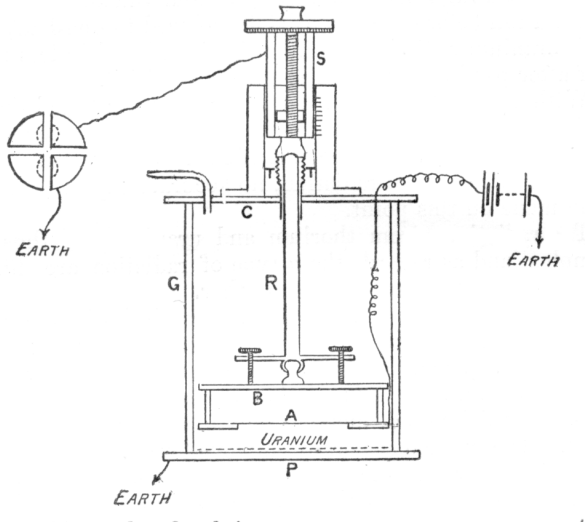

Figure 3:

§ 8 *Absorption of Uranium Radiation by Gases.*

The α radiation from uranium and its compounds is rapidly absorbed in its passage through gases. The absorption for hydrogen, air, and carbonic acid was determined, and was found to be least in hydrogen and greatest in carbonic acid. To show the presence of absorption, the following arrangement (fig. 3) was used : —

A layer of uranium–potassium sulphate or uranium oxide was spread uniformly over a metal plate P, forming a lamella of 11 cm. diameter. A glass vessel G, 12 cm. in diameter, was placed over the layer. Two parallel metal plates A and B, 1.5 cm. apart, "were insulated from each other by ebonite rods. A circular opening 7 cm. in diameter was cut in the plate A, and the opening covered by a sheet of aluminium foil 0.0005 cm. thick. The plate B was connected through a rod to a screw adjustment S, so that the condenser AB could be moved as a whole parallel to the base–plate. The system AB was adjusted parallel to the uranium surface and did not rotate with the screw. The rod R passed through
a short glass tube fixed in the ebonite plate C. A short niece of indiarubber tubing T was passed over the glass tube and a projecting flange in which the rod R was screwed. This served the same purpose as the usual stuffing–box, and allowed the distance of AB from the uranium to be adjusted under low

pressures.

The plate A was connected to one pole of a battery of 60 volts, the other pole of which was to earth. The plate B was connected through the screw to one pair of quadrants of an electrometer, the other pair of which was to earth. In order to avoid the collection of an electrostatic charge on the glass surface due to the conduction between the uranium and the glass near it, it was found very necessary to coat the inside of the glass cylinder with tinfoil. The tinfoil and base–plate P were connected to earth.

Since the surface of the uranium layer may be supposed to be giving out radiation uniformly from all parts, the intensity of the radiation at points near the centre of the uranium surface should be approximately uniform. If there were no absorption of the radiation in the gas, we should expect the intensity of the radiation to vary but slightly with distances from the surface small compared with the diameter of the radiating surface.

The radiation passing through the aluminium produces conductivity between A and B (fig. 3), and the rate of leak depends n the intensity of the radiation which has passed through a certain thickness of gas and the aluminium foil. As the system AB is moved from the base–plate, if there is a rapid absorption of the radiation in the gas, we should expect the rate of leak to fall off rapidly, and this is found to be the case. The following table gives the results obtained for air, hydrogen, carbonic acid, and coal–gas. For the first reading the distance d of the aluminium foil from the base-plate was about 3.5 mm.

Distance of Al foil from Uranium	Rate of Leak between plates			
	Hydrogen	Air	Carbonic Acid.	Coal–gas
d	1	1	1	1
d + 1.25 mm.	...	...	0.74	...
d + 2.5 mm	...	0.67	0.57	0.81
d + 3.75 mm	...	...	0.41	...
d + 5 mm	0.84	0.45	0.32	0.63
d + 7.5 mm	...	0.31	...	...
d + 10 mm	0.67	0.21	...	0.39
d + 15 mm	0.53	...	...	0.22

The rate of leak for the distance d is taken as unity in each gas for the purpose of comparison. The actual rates of leak between A and B for the distance d is given in the following table:—

Gas	Rate of Leak in scale–divisions per min.
Hydrogen	25
Coal–gas	35
Air	28
Carbonic acid	18

The results of the previous table are shown graphically in fig. 4, where the ordinates represent currents and the abscissæ
distances from the base–plate. It will be seen that the current decreases most rapidly in carbonic acid and least in hydrogen. As the distance from the base–plate increases in arithmetical progression, thy rate of leak diminishes approximately in geometrical progression. The rapid decrease of the current is due to the absorption of the radiation in its passage through the gas. The decrease of the current in air at 190 mm. pressure is also shown in the figure. Since the absorption is smaller for air at this pressure than at normal pressure, the rate of leak diminishes much more slowly with the distance.

In the above experiments both the α and β radiations produce conductivity in the gas. A thin layer of uranium oxide was, however, used, and in that case the rate of leak due to the β radiation may be neglected in comparison with that produced by the α radiation.

The results that have been obtained on the variation of the rate of leak with distance may be simply interpreted on the theory of the ionization of the gas through which the radiation passes. It is assumed that the rate of ionization proportional to the intensity of the radiation (as is the case in Röntgen–ray conduction), and that the intensity of the radiation near the uranium surface is constant over a plane parallel to that surface. This is very approximately the case if the distance from the uranium surface is small compared with the diameter of the radiating surface.

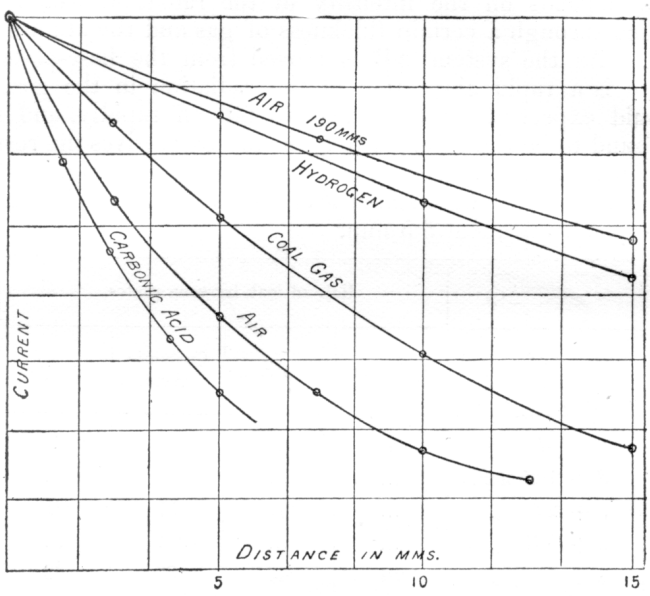

Figure 4:

For simplicity we will consider the case of an infinite plane of uranium giving out homogeneous radiation.

If I be the intensity of the radiation close to the uranium surface, the intensity at a distance x is equal to $Ie^{-\lambda x}$ where λ, is the coefficient of absorption of the gas. The intensity is diminished in passing through the layer of aluminium foil A (fig. 3) in a constant ratio for all distances from the uranium. The intensity at a distance x after passing through the aluminium is thus $kIe^{-\lambda x}$ where k is a constant. The rate of production of the ions between two parallel planes between A and B (fig. 3) at distances $x + dx$ and x from the uranium is therefore proportional to $kIe^{-\lambda x}dx$. If τ be the distance of A from the uranium, and l the distance between A and B, the total number of ions produced per second between A and B is proportional to

$$\int_{\tau}^{l+\tau} Ike^{-\lambda x}dx,$$

or to

$$\frac{kI}{\lambda} \quad e^{-\lambda\tau} \quad \left\{1 - e^{-\lambda l}\right\}.$$

When a "saturating" electromotive force (see § 16) acts between A and B,

the current is proportional to the total number of ions produced. Now, as the system AB is moved from the radiating surface, $\frac{kl}{\lambda}\ (1 - e^{-\lambda l})$ is a constants for any particular gas. We thus see that the rate of leak is proportional to $e^{-\lambda\tau}$, or the rate of leak decreases in geometrical progression.

This result allows us to at once deduce the value of the coefficient of absorption for different gases from the data we have previously given.

The results are given in the following table:—

Gas	Value of λ
Hydrogen	0.43
Air	1.6
Carbonic acid	2.3
Coal–gas	0.93

or, to express the same results in a different way, the intensity of the radiation from an infinite plane of uranium is reduced by absorption to half its value after having passed through

3 mm. of carbonic acid,
4.3 mm. of air,
7.5 mm. of coal–gas,
16.3 mm. of hydrogen.

We see that the absorption is least in hydrogen and greatest in carbonic acid, and follows the same order as the density of the gases.

The values given above are for the α radiation. The β radiation is not nearly so rapidly absorbed as the α, but, on account of the small electrical leakage produced in its passage through the gas, it was not found feasible to measure the absorption in air or other gases.

The absorption of the α radiation by gases is very much greater than the absorption of rays from an ordinary Crookes' tube. In a previous paper[11] it has been shown that the value of λ for the radiation from the particular bulb used was 0.01. The absorption coefficient for the radiation is 1.6, or

[11] Phil. Mag. April 1897.

160 times as great. The absorption of the β radiation in gases is probably of the same order as the absorption for ordinary x–rays.

§ 9 *Variation of Absorption with Pressure.*

The absorption of the α radiation increases with increase of pressure and very approximately varies directly as the pressure.

The same apparatus was used as in fig. 3, and the vessel was kept connected to an air–pump. The variation of the rate of leak between A and B for different distances from the base–plate was determined for pressures of 760, 370, and 190 mm., and the results are given below:—

Distance of A from Uranium	Rate of Leak between plates		
	Air 760 mm.	Air 370 mm.	air 190 mm.
d (=3.5 mm.)	1	1	1
$d + 2.5$ mm	67	...	...
$d + 5$ mm	0.45	0.71	...
$d + 7.5$ mm	0.31	...	0.78
$d + 10$ mm	0.21	0.51	...
$d + 12.5$ mm	0.16	...	...
$d + 15$ mm.	...	0.36	0.59

Fur the purpose of comparison the rate of leak at the distance d is taken as unity in each case. It can readily be deduced from the results that the intensity of the radiation is reduced to half its value after passing through

4.3 mm. of air at 760 mm.
10 mm. of air at 370 mm.
19.5 mm. of air at 190 mm.

The absorption is thus approximately proportional to the pressure for the range that has been tried. It was not found feasible to measure the absorption at lower pressures on account of the large distances through which the radiation must pass to be appreciably absorbed.

A second method of measuring the absorption of the radiation in gases which depends on the variation of the rate of leak between two plates as the distance between them is varied, is given in § 12.

§ 10 *Effect of Pressure on the Rate of Discharge.*

Becquerel[12] has given a few results for the effects of pressure, and showed that the rate of leak due to uranium diminished with the pressure. Beattie and S. de Smolan[13] also investigated the subject, and came to the conclusion that in some cases the rate of leak varied as the pressure, and in others as the square root of the pressure, according to the voltage employed. Their tabulated results, however, do not show any close agreement with either law, and in fact, as I hope to show later, the relation between the rate of leak and the pressure is a very variable one, depending to a large extent on the distances between the uranium and the surrounding conductors, as well as on the gas employed. The subject is greatly complicated by the rapid absorption of the radiation by gases, but all the results obtained may be interpreted on the assumption that the rate of production of ions at any point varies directly as the *intensity* of the radiation and the *pressure* of the gas.

To determine the effects of pressure, an apparatus similar to fig.3 was used, with the difference that the plate A was removed. The uranium compound was spread uniformly over the central part of the lower plate. The movable plate, which was connected with the electrometer, was 10cm, the in diameter and moved parallel to the uranium surface. The base–plate was connected to one pole of a battery of 100 volts, the other pole of which was connected to earth. The rate of movement of the electrometer–needle was taken as a measure of the current between the plates. In some cases the uranium compound was covered with a thin layer of aluminium foil, but although this diminished the rate of leak the general relations obtained were unaltered.

The following tables give the results obtained for air hydrogen, and carbonic acid at different pressures with a potential–difference of 100 volts between the plates—an amount sufficient to approximately "saturate" the

[12] Comptes Rendus, p. 438 (1897)
[13] Phil. Mag. XLIII. p. 418 (1897)

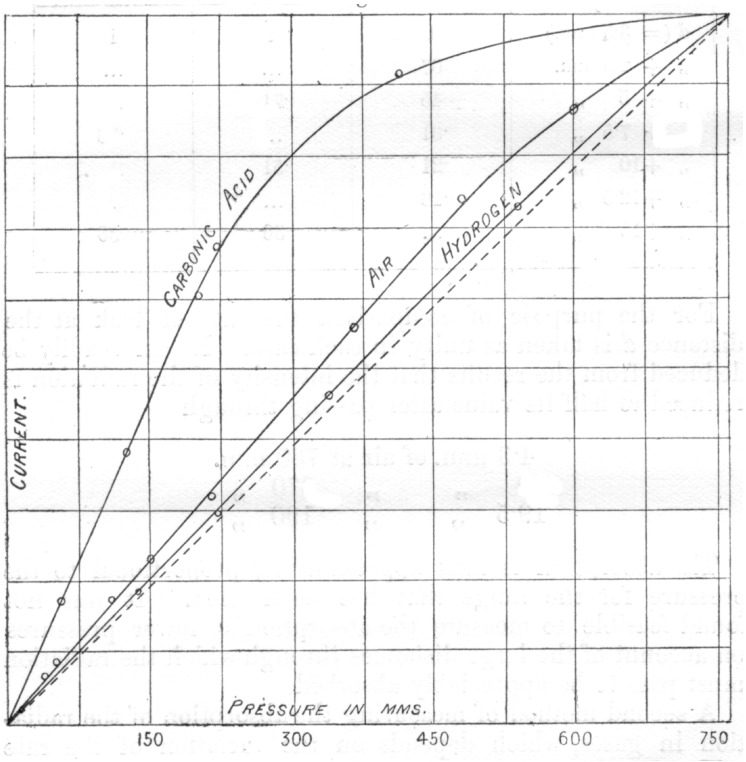
CARBONIC ACID
AIR
HYDROGEN
CURRENT.
PRESSURE IN MMS.
150
300
450
600
750

Figure 5:

gases air and hydrogen. Much larger voltages are required to produce approximate saturation for carbonic acid.

Air: Uranium oxide on base–plate. Plates about 3.5 mm apart.

Air.

Pressure	Current
mm.	
760	1
600	0.86
480	0.74
365	0.56
210	0.32
150	0.23
100	0.17
50	0.88
35	0.062

For hydrogen and carbonic acid. Plates about 3.5 mm apart.

Hydrogen.

Pressure	Current
mm.	
760	1
540	0.73
335	0.46
220	0.29
135	0.18

Carbonic Acid.

Pressure	Current
mm.	
760	1
410	0.92
220	0.69
125	0.38
55	0.175

The current at atmospheric pressure is in each case taken as unity for comparison, although the actual rates of leak were different for the three gases. Fig. 5 (p. 130???) shows these results graphically, where the ordinates represent current and the abscissaæpressure. The dotted line shows the position of the curve if the rate of leak varied directly as the pressure. It will be observed that for all three gases the rate of leak first of all increases directly as the pressure, and then increases more slowly as the pressure increases. The difference is least marked in hydrogen and most marked in carbonic acid. In hydrogen the rate of leak is nearly proportional to the pressure.

The relation between the rate of leak and the pressure depends also on the distance between the plates. The following few numbers are typical of the results obtained. There was a potential–difference of 200 volts between the plates and the rate of leak is given in scale–divisions per mm.

Pressure	Rate of Leak	
	Distance between plates 2.5 mm.	Distance between plates 15 mm.
mm.		
187	11	47
376	21	83
752	41	127

For small distances between the plates the rate of leak is more nearly proportional to the pressure than for large distances.

The differences between the results for various gases and for different distances receive a simple explanation if we consider that the intensity of the radiation falls off rapidly between the plates on account of the absorption in the gas. The tables given for the relation between current and pressure, where the distance between the plates is small, show that when the absorption is small, the rate of leak varies directly as the pressure. For small absorption the intensity of the radiation is approximately uniform between the plates, and therefore the ionization of the gas is uniform throughout the volume of the gas between the plates. Since under a saturating electromotive force the rate of leak is proportional to the total ionization, the above

experiments show that the rate of production of the ions at any point is proportional to the pressure. It has been previously shown that the absorption of the radiation is approximately proportional to the pressure.

Let q = rate of production of the ions near the uranium surface for unit pressure.

λ_0 = coefficient of absorption of the gas for unit pressure.

The total number of ions produced between the plates, distant d apart, per unit area of the plate is therefore easily seen to be equal to or to

$$pq \int_0^d e^{-p\lambda_0 x} dx;$$

or to

$$\frac{q}{\lambda_0} \left(1 - e^{-p\lambda_0 d}\right),$$

since we have shown that the ionization and absorption are proportional to the pressure. If there is a saturating electromotive force acting on the gas, the ratio of the rate of leak at the pressure p_1 to that at the pressure p_2 is equal to the ratio τ of the total number of ions produced at the pressure p_1 to the total number at pressure p_2 and is given by

$$\tau = \frac{1 - e^{-p_1\lambda_0 d}}{1 - e^{-p_2\lambda_0 d}}.$$

Now $p_1\lambda_0$ is the coefficient of absorption of the gas for the pressure p_1. If the absorption is small between the plates $p_1\lambda_0 d$ and $p_2\lambda_0 d$ are both small and the value of τ reduces to

$$\tau = \frac{p_1}{p_2},$$

or the rate of leak when the pressure is small is proportional to the pressure.

If the absorption is large between the plates at both the pressures p_1 and p_2 the value of τ is nearly unity – i.e. the rate of leak is approximately independent of the pressure. Experimental results on this point are shown fig. 7 (p. 138???)

For intermediate values of the absorption, the value of τ changes more slowly than the pressure.

With the same distance between the plates, the difference between the curves (fig. 5) for air and hydrogen is due to the greater absorption of the radiation by the air. The less the absorption of the gas, the more nearly is the rate of leak proportional to the pressure. For carbonic acid the rate of leak decreases far more slowly with the pressure than for hydrogen; this is due partly to the much greater value of the absorption in carbonic acid

and partly to the fact that 100 volts between the plates was not sufficient to saturate the gas,

If we take the rate of leak between two parallel plates some distance from the source of radiation, we obtain the somewhat surprising result that the rate of leak increases at first with diminution of pressure, although a saturating electromotive force is applied.

The arrangement used was very similar to that in fig. 3. The rate of leak was taken between the plates A and B, which were 2 cm, apart, and the plate A was about 1.5 cm. from the uranium surface. The following table gives the results obtained: —

Pressure	Current
mm.	
760	1
645	1.46
525	2
380	2.2
295	2.05
180	1.6
100	1.04
49	0.58

The current at atmospheric pressure is taken as unity. The results are represented graphically in fig. 6.

The rate of leak reaches a maximum at a pressure of less than half an atmosphere, and then decreases, and at a pressure of 100 mm. the rate of leak is still greater than at atmospheric pressure.

This result is readily explained by the great absorption of the radiation at atmospheric pressure and the diminution of absorption with pressure.

Let d_1 = distance of plate A from the uranium.
d_2 = distance of plate B from the uranium.

With the notation previously used,the total ionization between A and B (on the assumption that the radiating surface is infinite in extent) is readily seen to be equal to

$$\frac{q}{\lambda}\left\{e^{-p\lambda_0 d_1} - e^{-p\lambda_0 d_2}\right\}.$$

This is a function of the pressure, and is a maximum when

$$d_1 e^{-p\lambda_0 d_1} - d_2 e^{-p\lambda_0 d_2} = 0,$$

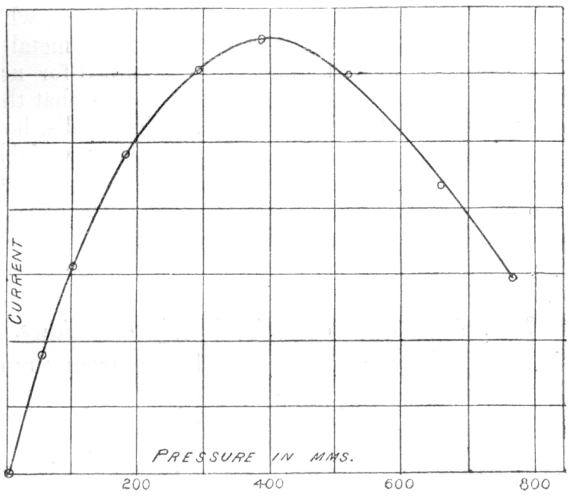

Figure 6:

i.e. when

$$\log_e \frac{d_1}{d_2} = -p\lambda_0 \ (d_2 - d_1).$$

The value of $p\lambda_0$ for air at 760 mm. is 1.6.

If $d = 3$ cm., $d_1 = 1$ the leak is a maximum when the pressure is about $^1/_3$ of an atmosphere. On account of the large distance of the plates from the uranium surface in the experimental arrangements, no comparison between experiment and theory could be made.

In all the investigations on the relation between the pressure and the rate of leak, large electromotive forces have been used to ensure that the current through the gas is proportional to the total ionization of the gas. With low voltages the relation between current and pressure would be very different, and would vary greatly with the voltage and distance between the electrodes as well as with the gas. It has not been considered necessary to introduce the results obtained tor small voltages in this paper, as they are very variable under varying conditions. Although they may all be simply explained on the results obtained tor the saturating electromotive forces they do not admit of simple calculation, and only serve to obscure the simple laws which govern the relations between ionization, absorption, and pressure. The general nature of the results for low voltages can be deduced from a consideration of the results given for the connexion (see § 16) between the current through the gas and the electromotive force acting on it at various pressures.

The above results for the relation between current and pressure may be compared with those obtained for Röntgen radiation. Perrin[14] found that the rate of leak varied directly as the pressure for saturating electromotive forces when the radiation did not impinge on the surface of the metal plates. This is in agreement with the results obtained for uranium radiation, for Perrin's result practically asserts that the ionization is proportional to the pressure. The results, however, of other experimenters on the subject are very variable and contradictory, due chiefly to the fact that in some cases the results were obtained for non–saturating electromotive forces, while, in addition, the surface ionization at the electrodes greatly complicated the relation, especially at low pressures.

§ 11 *Amount of Ionization in Different Gases.*

It has been shown that the α radiation from uranium is rapidly absorbed by air and other gases. In consequence of this the total amount of ionization produced, when the radiation is completely absorbed, can be determined.

The following arrangement was used:– A brass ball 2.2 cm. in diameter was covered with a thin layer of uranium oxide. A thin brass rod was screwed into it and the sphere was fixed centrally inside a bell–jar of 13 cm. diameter, the brass rod passing through an ebonite stopper. The bell–jar was fixed to a base–plate, and was made air–tight. The inside and outside of the bell–jar were covered with tinfoil. In practice an E.M.F. of 800 volts was applied to the outside of the bell–jar. The sphere, through the metal rod, was connected to one pair of quadrants of an electrometer. It was assumed that, with such a large potential–difference between the bell–jar and the sphere, the gas was approximately saturated and the rate of movement of the electrometer-needle was proportional to the total number of ions produced in the gas. The following were some of the results obtained, the rate of leak due to air being taken as 100.

[14] Comptes Rendus, CXXIII. p. 878.

Gas	Total Ionization
Air	100
Hydrogen	95
Oxygen	106
Carbonic Acid	96
Coal–gas	111
Hydrochloric Acid Gas	102
Ammonia Gas	101

The results for hydrochloric acid and ammonia are only approximate, for it was found that both gases slightly altered the radiation emitted by the uranium oxide. For example, before the introduction of the gas the rate of leak due to air was found to be 100 divisions in 69 sec.; after the introduction of hydrochloric acid 100 divisions in 72 sec.; and with air again after the gas was removed 100 divisions in 74 sec.

The rate of leak is greatest in coal–gas and least in hydrogen, but all the gases tried show roughly the same amount of ionization as air. In the case considered both kinds of radiation emitted by uranium are producing ionization in the gas. By covering over the uranium oxide with a few layers of thin tinfoil it was found that, for the arrangement used, the rate of leak due to the penetrating ray was small in comparison with the rate of leak due to the α radiation.

The effect of diminution of the pressure on the rate of leak for air, hydrogen, and carbonic acid is shown in fig. 7, where the abscissærepresent pressure and the ordinates rate of leak. In the case of air and carbonic acid it was found that the rate of leak slightly increased at first with diminution of pressure. This was ascribed to the fact that even with 800 volts acting between the uranium and the surrounding conductor the saturation for atmospheric pressure was not complete. It will be observed that the rate of leak in air remains practically constant down to a pressure of 400 mm., and for carbonic acid down to a pressure of 200 mm. In hydrogen, however, the change of rate of leak with pressure is more rapid, and shows that all the radiation emitted by the uranium was nut completely absorbed at atmospheric pressure, so that the total ionization is probably larger than the

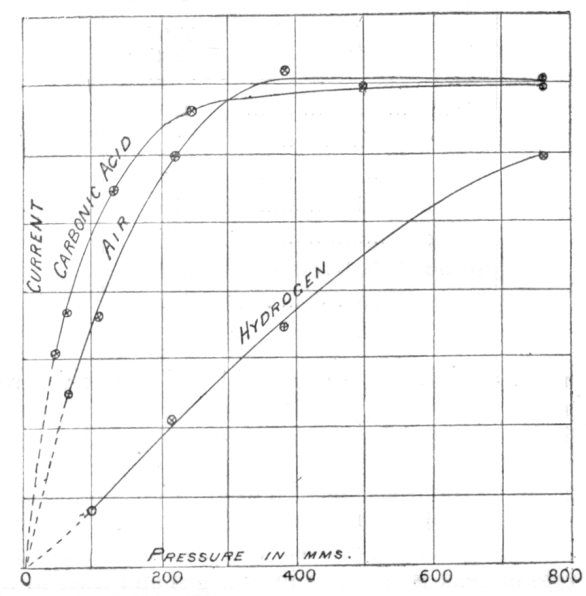

Figure 7:

value given in the table.

Assuming that there is the same energy of radiation emitted whatever the gas surrounding the uranium and that the radiation is almost completely absorbed in the gas, we see that there is approximately the same amount of ionization in all the gases for the same absorption of energy. This is a very interesting result, as it affords us some information on the subject of the relative amounts of energy required to produce ionization in different gases. In whatever process ionization may consist there is energy absorbed, and the energy required to produce a separation of the same quantity of electricity (which is carried by the ions of the gas) is approximately the same in all the gases tried.

From the results we have just given, it will be seen how indefinite it is to speak of the conductivity of a gas produced by uranium radiation. The. ratio of the conductivities for different gases will depend very largely on the distance apart of the electrodes between which the rate of leak is observed. When the distance between the electrodes (e.g. two parallel plates) is small, the rate of leak is greater in carbonic acid than in air, and greater in air than in hydrogen. As the distance between the plates is increased, these valuer tend to approximate equality. If, however, the rate of leak is taken between

two plates some distance from the radiating surface (e.g. the plates A and B in fig. 3), the ratio of the rates of leak for different gases will depend on the distance of the plate. A from the surface of the uranium. If the plate A is several centimetres distant from the uranium, the rate of leak will be greater with hydrogen than with air, and greater in air than in carbonic acid – the exact reverse of the other case. These considerations will also apply to what is meant by the conductivity of a gas for uranium radiation.

In a previous paper[15] I found the coefficient of absorption of a gas for Röntgen rays to be roughly proportional to the conductivity of the gas. The conductivity in this case was measured by the rate of leak between two plates close together and not far from the Crookes tube. The absorption in the air between the bulb and the testing apparatus was small. If it were possible to completely absorb the Röntgen radiation in a gas and measure the resulting conductivity, the total current should be independent of the gas in which the radiation was absorbed. This result follows at once if the absorption is proportional to the ionization produced for all gases. The results for uranium and Röntgen radiation are thus very similar in this respect.

§ 12 *Variation of the Current between two Plates with the Distance between them.*

The experimental arrangement adopted was similar to that in fig. 3 with the plate A removed. Two horizontal polished zinc plate 10 cm. in diameter were placed inside a bell–jar. The lower plate was fixed and covered with a uniform layer of uranium oxide, and the upper plate movable, by means of a screw, parallel to the lower plate. The bell–jar was air–tight, and was connected with an air–pump. The lower plate was connected to one pole of a battery of 200 volts, the other pole of which was earthed, and the insulated top plate was connected with the electrometer. The exterior surface of the glass was covered with tinfoil connected to earth.

The following table gives the results of the variation of the rate of leak with distance for air at pressures of 752, 376, and 187 mm. The results have been corrected for change of the capacity of the electrometer with movement of the plates.

[15] Phil. Mag. April 1897

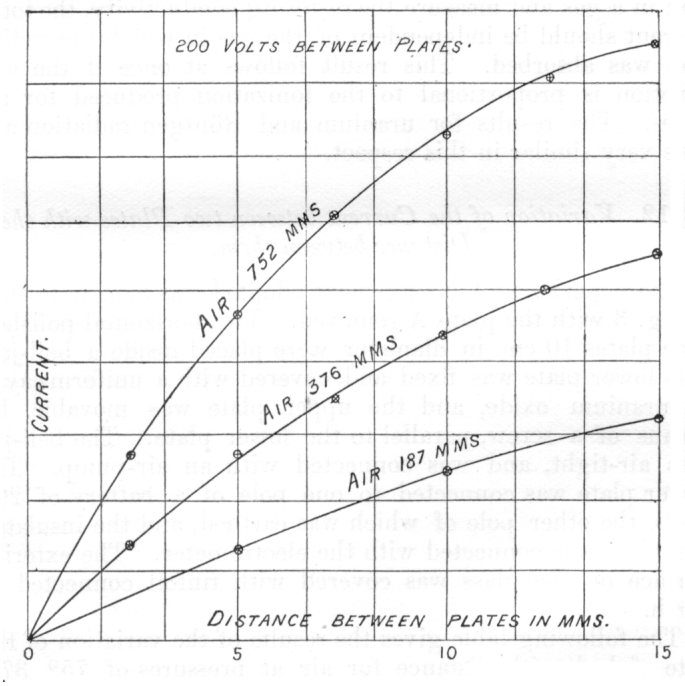

Figure 8:

Distance between plates	Rate of Leak in scale-divisions per min.		
	752 mm.	376 mm.	187 mm
mm.			
2.5	41	21	
5	70	40	20
7.5	92	53	
10	109	65	36
12.5	123	76	
15	128	83	47

The results are shown graphically in fig. 8, where the abscissærepresent distances between the plates and the ordinates rates of leak. The values given above correspond to saturation rates of leak; for

200 volts between the plates is sufficient to very approximately saturate the gas even for the greatest distance apart of 1.5 cm. It will be observed that the rate of leak increases nearly proportionally to the distance between the plates for short distances, but for air at atmospheric pressure increases very slowly with the distance when the distances are large. If there were no appreciable absorption of the radiation by the gas, the ionization would be approximately uniform between the plates, provided the diameter of the uranium surface was large compared with the greatest distance between the plates. The saturation rate of leak would in that case vary as the distance. If there is a large absorption of the radiation by the gas, the ionization will be greatest near the uranium and will fall off rapidly with the distance. The saturation rate of leak will thus increase at first with the distance, and then tend to a constant value when the radiation is completely absorbed between the plates.

The results given in the previous table allow us to determine the absorption coefficient of air at various pressures. My attention was first drawn to the rapid absorption of the radiation by experiments of this kind.

The number of ions produced between two parallel plates distant d apart is equal to

$$pq \int_0^d e^{-p\lambda_0 x} dx,$$

i.e., to

$$\frac{q}{\lambda_0} (1 - e^{-p\lambda_0 d}),$$

assuming the ionization and the absorption are proportional to the pressure. The notation is the same as that used in § 10.

For the pressure p the saturation rate of leak between the plates is thus proportional to $1 - e^{-p\lambda_0 d}$.

If p and d are varied so that $p \times d$ is a constant, the rate of leak should be a constant. This is approximately true as the numbers previously given (see fig. S) show. It must, however, be borne in mind that the conditions, on which the calculations are based, are only approximately fulfilled in practice, for we have assumed the uranium surface to be infinite in extent and that the saturation is complete.

The variation of the rate of leak with distance agrees fairly closely with the theory. When $p\lambda_0 d$ is small the rate of leak is nearly proportional to the distance between the plates and the pressure of the gas. When $p\lambda_0 d$ is large the rate of leak varies very slowly with the distance.

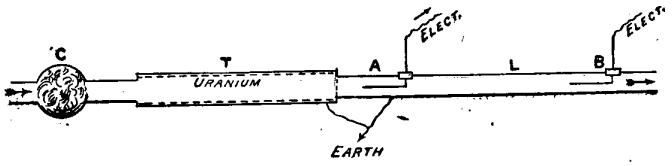

Figure 9:

The value of $p\lambda_0$ can be deduced from the experimental results, so that we have here an independent method of determining the absorption of the radiation at different procures.

The lower the pressure the more uniform is the ionization between the plates, so that the saturation rate of leak at low pressures is nearly proportional to the distance between the plates. This is seen to be the case in fig. 8, where the curve for a pressure of 187 mm. is approximately a straight line. Similar results have been obtained for hydrogen and carbonic acid.

§ 13 *Rate of Recombination of the Ions.*

Air that has been blown by the surface of a uranium compound has the power of discharging both positive and negative electrification. The following arrangement was used to find the duration of the after–conductivity induced by uranium radiation:— A sheet of thick paper was covered over with a thin layer of gum–arabic, and then uranium oxide or uranium potassium sulphate in the form of fine powder was sprinkled over it. After this had dried the sheet of paper was formed into a cylinder with the uranium layer inside. This was then placed in a metal tube T (fig. 9) of 4 cm. diameter. A
blast of all air from a gasometer, after passing through a plug C of cotton–wool to remove dust, passed through the cylinder T and then down a long metal tube connected to earth.

Insulated electrodes A and B were fixed in the metal tube. The electrometer could be connected to either of the electrodes A or B. In practice the quadrants of the electrometer were first connected together. The electrode A or B and the electrometer were then charged up to a potential of 30 volts, and the quadrants then separated.

When the uranium was removed there was no rate of leak , it either A or

B when a rapid current of air was sent through the tube. On replacing the uranium cylinder and sending a current of air along the tube, the electrometer showed a gradual loss of charge which continued until the electrode was discharged.

When the electrode A was charged to 30 volts there was no rate of leak of B. The rate of leak of B or A is thus proportional to total number of ions in the gas. The ions recombine in the interval taken for the air to pass between A and B. The rate of leak of B for a saturating voltage, when A is to earth, is thus less than that of A.

For a particular experiment the rate of leak of the electrode A was 146 divisions per minute. When A was connected to earth, the saturation rate of leak of B was 100 divisions per minute. The distance between A and B was 44 cm., and the mean velocity of the current of air along the tube 70 cm. per second. In the time, therefore, of 0.63 sec. the conductivity of the gas has fallen to 0.68 of its value.

If we assume, as in the case of Röntgenized air[16], that the loss of conductivity is due to the recombination of the ions, the variation of the number with the time is given by

$$\frac{dn}{dt} = -\alpha n^2,$$

where n is the number of ions per c.c. and a α a constant. If N is the number of ions at the electrode A, the number of ions n at B after an interval t is given by

$$\frac{1}{n} = \frac{1}{N} = \alpha t.$$

Now the saturating rates of leak at A and B are proportional to N and n, and it can readily he deduced that the time taken for the number of ions to recombine to half their number is equal to 1.3 sec. This is a much slower rate of recombination than with Röntgenized air near an ordinary Crookes tube.

The amount of ionization by the uranium radiation is in general much smaller than that due to Röntgen rays, so that the time taken for the ions to fall to half their number is longer.

The phenomenon of recombination of the ions is very similar in both uranium and Röntgen conduction. In order to test whether the rate of recombination of the ions is proportional to the square of the number present in the gas, the following experiment was performed:–

A tube A (fig. 10) was taken, 3 metres long and 5.5 cm. in diameter. A cylinder D, 25 cm. long, had its interior surface coated with uranium oxide.

[16]Phil. Mag. Nov. 1897

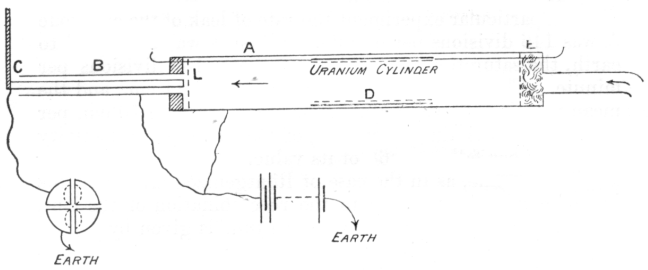

Figure 10:

This cylinder just fitted the large tube, and its position in the tube could be varied by means of strings attached to it, which passed through corks at the ends of the long tube. The air was forced
through the tube from a gasometer, and on entering the tube A passed through a plug of cotton–wool, E, in order to remove dust from the air and to make the current of air more uniform over the cross–section of the tube. The air passed by the uranium surface aim then through a gauze L into the testing cylinder B of 2.8 cm. diameter. An insulated rod C, 1.6 cm. in diameter, passed centrally through the cylinder B and was connected with the electrometer. The cylinders A and B were connected to one pole of a battery of 32 volts, the other pole of which was to earth.

The potential–difference of 32 volts between B and C was sufficient to almost completely remove all the ions from the gas in their passage along the cylinder. The rate of leak of the electrometer was thus proportional to the number of ions in the gas

The following rates of leak were obtained for different distances of the uranium cylinder from the gauze L (table, page 145???).

The first column of the table gives the distances of the end of the uranium cylinder from the gauze L. d (about 20 cm.) was the distance for which the first measurement was made. In the second column the time intervals taken for the air to pass over the various distances are given. The value of t corresponds to the distance d. The mean velocity of the current of air along the tube was about 25 cm. per sec.

Distance of Uranium cylinder from L	T	Rate of leak in scale–divisions per minute	Calculated rates of leak
d	t	$*159$	$*159$
$d + 25$ cm.	$t + 1$ sec.	111	112
$d + 50$ cm.	$t + 2$ sec.	$* 87$	$* 87$
$d + 100$ cm.	$t + 4$ sec.	62	60
$d + 200$ cm.	$t + 8$ sec.	39	37

In the third column are given the observed rates of leak, and in the fourth column the calculated values.

The values were calculated on the assumption that the rate of recombination of tho ions was proportional to the square of the number present, i.e. that

$$\frac{dn}{dt} = -\alpha n^2,$$

Where n is the number of ions present and α is a constant. The two numbers with the asterisk were used to determine the constant of the equation. The agreement of the other numbers is closer than would be expected, for in practice the velocity of the blast is not constant over the cross–section, and there is also a slight loss of conductivity of the gas due to the diffusion of the ions to the side of the long tube.

It will be observed that the rate of recombination is very slow when a small number of ions are present in the gas, and that the air preserves one quarter of its conducting power after an interval of 8 seconds.

§ 14 *Velocity of the Ions.*

The method[17] adopted to determine the velocity of the ions in Röntgen conduction cannot be employed for uranium conduction. It is not practicable to measure the rate of recombination of the ions between the plates on

[17] Phil. Mag. Nov. 1897.

account of the very small after–conductivity in such a case; and, moreover the inequality of the ionization between the two plates greatly disturbs the electric field between the plates.

A comparison of the velocities, under similar conditions, of the ions in Röntgen and uranium conduction can, however be readily made. The results show that the ions in the two types of conduction are the same.

In order to compare the velocities an apparatus similar to fig. 10 was used. The ions were blown by a charged wire A, and the conductivity of the gas tested immediately afterwards at an electrode B, which was fixed close to A. The electrode A was cylindrical and fixed centrally in the metal tube L, which was connected to earth. For convenience of calculation it is assumed that the electric field between the cylinders is the same as if the cylinders were infinitely long.

Let a, b be the radii of the electrode A and the tube (internal);

Let V be the potential of A (supposed positive).

The electromotive intensity X (without regard to sign) at a distance τ from the centre of the tube is given by

$$X = \frac{V}{\tau \log_e \frac{b}{a}}.$$

Let u_1, u_2 be the velocities of the positive and negative ions for a potential gradient of 1 volt per cm. If the velocity is proportional to the electric force at any point, the distance $d\tau$ traversed by the negative ion in the time dt is given by

$$d\tau = X u_2 \, dt,$$

or

$$dt = \frac{\log_e \frac{b}{a} \, \tau d\tau}{V u_2}.$$

Let τ be the distance from the centre from which the negative ion can just reach the electrode in the time t taken for the air to pass along the electrode.

Then

$$t = \frac{(\tau_2^2 - a^2)}{2V u_2} \log_e \frac{b}{a}.$$

If ρ_2 be the ratio of the number of the negative ions that reach the electrode A to the total number passing by, then

$$\rho_2 = \frac{\tau_2^2 - a^2}{b^2 - a^2}.$$

Therefore

$$u_2 = \frac{\rho_2(b^2 - a^2)\ \log_e \frac{b}{a}}{2V \cdot t} \tag{1}$$

Similarly the ratio ρ_1 of the number of positive ions that give up their charge to the external cylinder to the total number is given by

$$u_1 = \frac{\rho_1(b^2 - a^2)\ \log_e \frac{b}{a}}{2V \cdot t}. \tag{2}$$

In the above equations it is assumed that the current of air is uniform over the cross–section of the tube, and that the ions are uniformly distributed over the cross–section; also, that the movement of the ions does not appreciably disturb the electric field. Since the value of t can be calculated from the velocity of the current of air and the length of the electrode, the values of the velocities of the ions under unit potential gradient can at once be determined.

The equation (1) shows that p_2 is proportional to V, – i.e., that the rate of leak of the electrode A, varies directly as the potential of A, provided the value of V is not large enough to remove all the ions from the gas as it passes by the electrode. This was experimentally found to be the case.

In the comparison of the velocities the potential V was adjusted to such a value that p_2 was about one half. This was determined by testing the rate of leak at B with a saturating electromotive force. The amount of recombination of the ions between the electrodes A and B was very small, and could be neglected.

The uranium cylinder was then removed, all the other parts of the apparatus remaining unchanged. An aluminium cylinder was substituted for the uranium cylinder, and x–rays were allowed to fall on the aluminium. The bulb and induction–coil were placed in a metal box in order to carefully screen off all electrostatic disturbances. The rays were only allowed to fall on the central portion of the cylinder. The intensity of the rays was adjusted so that, with the same current of air, the rate of leak was comparable with that produced by the uranium. It was then found that the value of p_2 was nearly the same as for the uranium conduction, For example, the rate of leak of B was reduced from 38 to 14 scale–divisions per min. by charging A to a certain small potential, when the air was blown by the surface of the uranium. When Röntgenized air was substituted, the rate of leak was reduced from 50 to 18 divisions per min. under the same conditions. The values of p_2 were 0.63 and 0.64 respectively. This agreement is closer than would be expected, as the bulb was not a very steady source of radiation.

This result shows that the ions in Röntgen and uranium conduction move with the same velocity and are probably identical. The velocity of an ion in passing through a gas is proportional to, e/m, where e is the charge carried by the ion, and m its mass. Unless e and m vary in the same ratio it follows that the charge carried by the ion in uranium and Röntgen conduction is the same, and also that their masses are equal.

It was found that the velocity of the negative ion was somewhat greater than that of the positive ion. This has been shown to be the case for ions produced by Röntgen rays.[18] The difference of velocity between the positive and negative carrier is readily shown. The rate of leak of B is observed when charged positively and negatively. When B was charged positively the rate of leak measured the number of negative ions that escaped the electrode A, and when charged negatively the number of positive ions. The rate of leak was always found to be slightly greater when B was charged negatively. This is true whether A is charged positively or negatively, and shows that there is an excess of positive ions in the gas after passing by the electrode A.

The difference of velocities of the ions can also readily be shown by applying an alternating electromotive force to the electrode A sufficient to remove a large proportion of the ions as the air passes by. The issuing gas is always found to be positively charged, showing that there is an excess of positive over negative ions.

A large number of determinations of the velocities of the uranium ions have been made, with steady and alternating electromotive forces, when the air passed between concentric cylinders or plane rectangular plates. In consequence of the inequality of the velocity of the current of air over the cross–section of the tube, and other disturbing factors which could not be allowed for, the determination could not be made with the accuracy that was desired. For an accurate determination, a method independent of currents of air is very desirable.

§ 15 *Potential Gradient between two Plates.*

The normal potential gradient between two plates is altered by the movement of the ions in the electric field.

Two methods were used to determine the potential gradient. In the first method a thin wire or strip was placed between two parallel plates one of which was covered with uranium. The wire was connected with the

[18] Zeleny, Phil. Mag. July 1898.

electrometer, and after being left some time took up the potential in the air close to the wire. In the second method the ordinary mercury – or water–dropper was employed to measure the potential at a point.

For the first method two large zinc plates were taken and placed horizontal and parallel to one another. A layer of uranium oxide was spread over the lower plate. The bottom plate way connected to one pole of a battery of 8 volts, and the top plate was connected to earth. An insulated thin zinc strip was placed between the plates and parallel to them. The strip was connected with the electrometer, and gradually took up the potential of the point. By moving tho strip the potential at different points between the plates could be determined.

The following table is an example of the results obtained.

Plates 4.8 cm. apart; 8 volts between plates.

Distance from top plate	Potential in volts with Uranium	Potential in volts without Uranium
0	0	0
0.6	2.5	1
12.2	3.8	2
2.1	5.9	3.5
3.1	7	5.2
4.8	8	8

The third column is calculated on the assumption that without the uranium the potential falls off uniformly between the plates.

The method given above is not very satisfactory when the strip is close to the plates, as it takes up the potential of the point very slowly.

The water– or mercury–dropper was more rapid in its action, and gave results very similar to those obtained by the first method. Two parallel brass plates were placed vertically and insulated. One plate was connected to the positive and the other to the negative pole of a battery. The middle point of the battery was placed to earth. The water–dropper was connected with the electrometer. The potential at a point was first determined without any

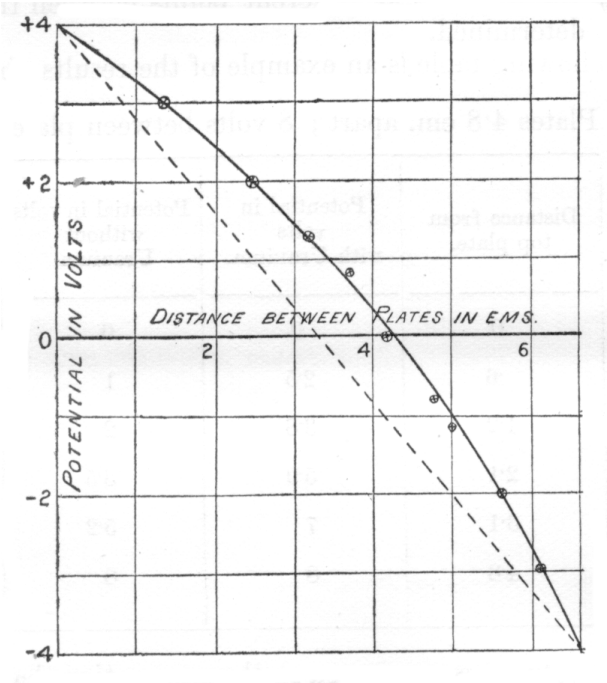

Figure 11:

uranium near. One plate was then removed, and an exactly similar plate, covered with the uranium compound, substituted. The potential of the point was then observed again. In this way the potential at any point with and without the uranium could be determined. The curve shown in fig. 11 is an example of the potential gradient observed between two parallel plates 6.6 cm. apart. The dotted line represents the potential gradient when the uranium is removed. The ordinates represent volts and the abscissædistances from the plate covered with the uranium compound.

It will be observed that the potential gradient is diminished near the uranium and increased near the other plate. The point of zero potential is displaced away from the uranium.

From curves showing the potential gradient between two plates, the distribution of free electrification between the plates can be deduced. By taking the first differential of the curve we obtain $\frac{dv}{dx}$, the electric force at any point, and by taking the second differential of the curve we obtain $\frac{d^2v}{dx^2}$, which is equal to $-4\pi\rho$, where ρ is the volume–density of electrification at any point. In order to produce the disturbance of the electric field shown in fig. 11,

there must be an excess of ions of one kind distributed between the plates. Such a result follows at once from what has been said in regard to the inequality of the ionization between the plates due to the absorption of the radiation.

It was found that the potential gradient approached more and more its undisturbed value with increase of the electromotive force between the plates. The displacement of the point of zero–potential from the uranium surface increased with diminution of electromotive force. For example, for two plates 51 mm. apart, charged to equal and opposite potentials, the points of zero potential were 28, 30, 33 mm. from the uranium when the differences of potential between the plates were 16, 8, and 4 volts respectively.

When the uranium was charged positively, the point, of zero potential was more displaced than when it was charged negatively. This is due to the slower velocity of the positive ion.

The slope of potential very close to the surface of the uranium has not been investigated. The deviation from the normal potential slope between the plates depends very largely on the intensity of the ionization produced in the gas. With very weak ionization the normal potential gradient is only slightly affected.

Child [19] and Zeleny[20] have shown that the potential gradient between two parallel plates exposed to Röntgen rays is not uniform. In their cases the ionization was uniform between the plates, and the disturbance in the field manifested itself in a sudden drop at both electrodes. In the case considered for uranium radiation, the ionization is too small for the effect to be appreciable. The disturbance of the field is due chiefly to the inequality of the ionization, and does not only take place at the electrodes.

§ 16 *Relation between Current and Electromotive Force.*

The variation with electromotive force of the current through a gas exposed to uranium radiation has been investigated by Becquerel[21] and later by de Smolan and Beattie.[22] The general relation between the current

[19] Wied. Annal. April 1898, p. 152.
[20] Phil. Mag., July 1898.
[21] Comptes. Rendus, pp. 438, 800 (1897).
[22] Phil. Mag. vol. XLIII. p. 418 (1897).

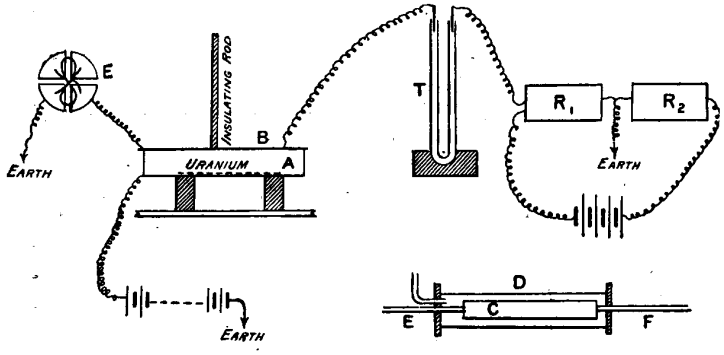

Figure 12:

through the gas and the E.M.F. acting on it is very similar to that obtained for gases exposed to Röntgen radiation. The current at first increases nearly proportionally with the E.M.F. (provided the E.M.F.'s of contact between the metals are taken into account), then more slowly, till finally a stage is reached, which may be termed the "saturation stage," where there is only a very slight increase of current with a very large increase of electromotive force. As far as experiment; have gone, uranium oxide, when immersed in gases which do not attack it, gives out a constant radiation at a definite temperature, and the variation of the intensity of radiation with the temperature over the ordinary atmospheric range is inappreciable. For this reason it is possible to do more accurate work with uranium radiation than with Röntgen radiation, for it is almost impossible to get a really steady source of x–rays for any length of time.

It was the object of these experiments to determine the relation between current and electromotive force with accuracy, and to see whether the gas really becomes saturated; i. e., whether the current appreciably increases with electromotive forces when the electromotive forces are great, but still not sufficient to break down the gas and to produce conduction in the gas without the uranium radiation.

A null method was devised to measure the current, in order to be independent of the electrometer as a measuring instrument and to merely use it as an indicator of difference of potential.

Fig, 12 shows the general arrangement of the experiment.

A and B were two insulated parallel zinc plates : on the lower plate A was spread a uniform layer of uranium oxide. The bottom plate was connected to one pole of a battery of a large number of storage–cells, the other pole

of which was to earth. The insulated plate B was connected to one pair of quadrants of an electrometer, the other pair of which was to earth. Under the influence of the uranium the air between the plates A and B is made a partial conductor, and the potential of B tends to become equal to that of A. In order to keep the potential of B at zero, B is connected through a very high resistance T of xylol, one end of which is kept at a steady potential. If the amount of electricity supplied to B through the xylol by the battery is equal and opposite in sign to the quantity passing between A and B, the potential of B will remain steadily at zero. In order to adjust the potential to be applied to one end of the xylol–tube T, a battery was connected through resistance–boxes R_1 R_2 the wire between being connected to earth. The ratio of the E.M.F. e acting on T to the E.M.F. E of the battery is given by

$$\frac{e}{E} = \frac{R_1}{R_1 + R_2}.$$

In practice $R_1 + R_2$ was always kept constant and equal to 10,000 ohms, and, in adjusting the resistance plugs taken from one box were transferred to the other. The value of e is thus proportional to R_1, and the amount of current supplied to B (assuming xylol obeys Ohm's Law) is proportional to R_1. If the resistances are varied till the electrometer remains at the "earth zero" the current between the plates is proportional to R_1. If the value of the E.M.F. applied is too great the needle moves in one direction, if too small in the opposite direction. For fairly rapid leaks the current could be determined to an accuracy of 1 per cent.; but for slow electromotive leaks this accuracy is not possible on account of slow changes of the electrometer zero when the quadrants are disconnected.

The following tables show the results of an experiment with uranium oxide. The surface of the uranium was 14 cm. square. In order to get rid of stray radiation at the sides lead strips, which nearly reached to the top plate, were placed round the uranium. 16 volts were applied to the resistance–box, and a resistance of 10,000 ohms kept steadily in the circuit.

Plates 2.5 cm. apart	
Volts	Current R_1
0.5	425
1	825
2	1570
4	2750
8	3750
16	4230
37.5	4700
112	5250
375	5625
800	5825

Plates 5 cm. apart	
Volts	Current R_1
0.125	1400
0.25	2800
0.5	4300
1	5250
2	5650
4	6200
8	6670
16	6950
100	7400
335	7850

Under the column of volts the difference of potential between A and B is given. The current is given in terms of the resistance R_1 required to keep the electrometer at the earth zero. It will be observed that for the first few readings Ohm's Law is approximately obeyed, and then the current increases more gradually till for large E.M.F.'s the rate of increase is very slow. For the platen 0.5 cm. apart the rate of leak for 335 volts is only 50 per cent. greater than the rate of leak for 1 volt.

The same general results are obtained if the surface of the uranium is bare or covered with thin metal. The disadvantages of covering the surface

with thin tin or aluminium foil are (1) that the intensity of the radiation is considerably decreased; (2) that the ions diffuse from under the tinfoil through any small holes or any slight openings in the side. The drawback of using the uncovered uranium in the form of fine powder, is that under large electric forces the fine uranium particles are set in motion between the plates and cause an additional leakage. In practice the rate of leak was measured with potential–differences too small to produce an y appreciable action of this kind.

In order to investigate the current–electromotive–force relations for different gases the same method was used, but the leakage in this case took place between two concentric cylinders. The apparatus is shown in the lower part of fig. 12: C and D were two concentric cylinders of brass 4.5 and 3.75 cm. in diameter, insulated from each other. The ends of the cylinder D were closed by ebonite collars, and the central cylinder was supported in position by brass rods passing through the ebonite. The surface C was uniformly covered with uranium oxide. The cylinder D was connected to one pole of a battery, the other pole of which was to earth. The cylinder C was connected to the electrometer. The following tables show the results obtained for hydrogen, carbonic, acid, and air. Distance between cylinders 0.375 cm.

Hadrogen		Carbonic Acid		Air	
Volts	Current	Volts	Current	Volts	Current
0	122	0	95	+ 1	418
- 0.62	125	- 0.125	205	2	451
0.125	123	0.25	255	4	495
0.25	142	0.5	305	8	533
5	150	1	355	36	601
1	160	2	405	108	615
2	163	4	460	216	630
4	165	8	520		
8	168	16	590		
16	172	36	705		
108	178	108	787		
216	185	216	820		

The above results are expressed graphically in fig. 13, where the or-

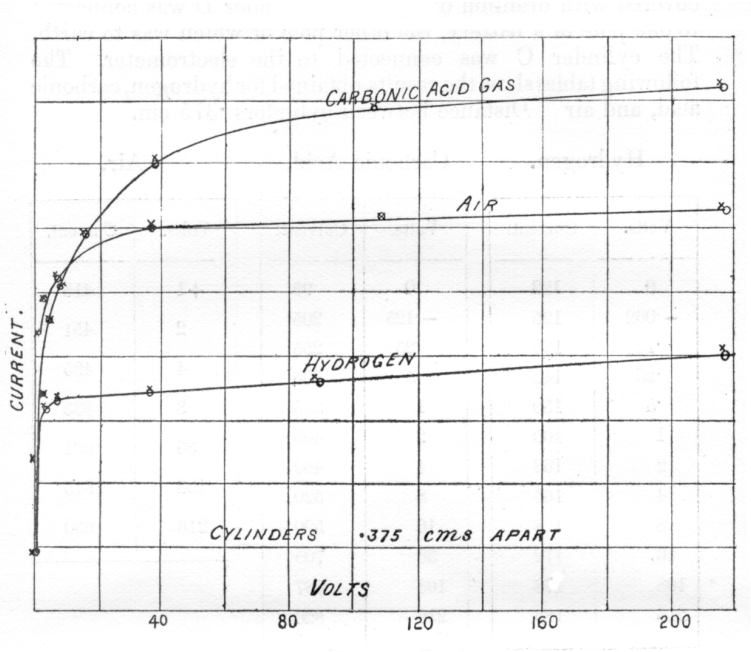

Figure 13:

dinates represent current on an arbitrary scale and the abscissaævolts. In the tables given for hydrogen and carbonic acid it will be observed that the current has a definite value when there is no external electromotive force acting. The reason for this is probably due to the contact difference of potential between the uranium surface and the interior brass surface of the outside cylinder. When the external cylinder was connected to earth the inside cylinder became charged[23] to — 0.12 volt after it was left a short time. In consequence of this action, for small electromotive forces the rates of leak are different for positive and negative.

Results of this kind are shown more clearly in fig. 14. which gives the current–electromotive–force carves for hydrogen and carbonic acid for small voltages. When there is no external electromotive force acting, the current has a fixed value; if the uranium is charged positively, the current increases

[23]This phenomenon has been studied by Lord Kelvin, Beattie, and S. de Smolan, and it has been shown that metals are charged up to small potentials under the influence of uranium radiation. The steady difference of potential between two metal plates between which the radiation falls is the same as the contact difference of potential. An exactly similar phenomenon has been studied by Perrin (Comptes Rendus, CXXIII. p. 496) for x–rays.

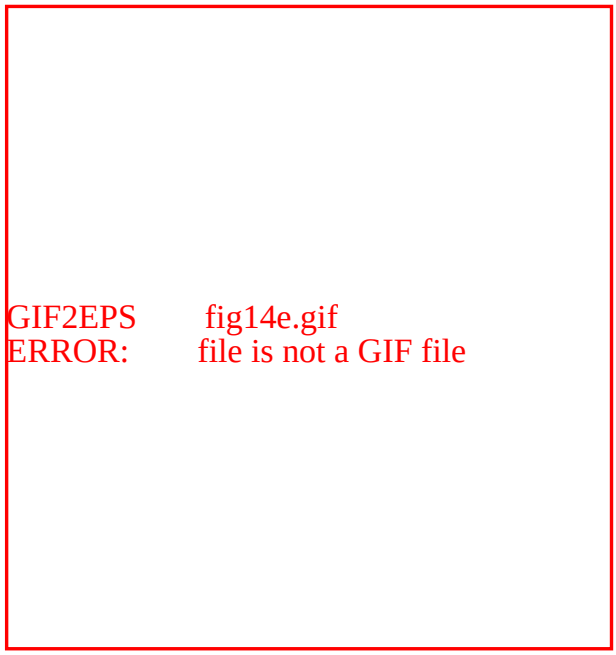

Figure 14:

slowly with the voltage; when the uranium is charged negatively, the current is at first reversed, becomes zero, and rapidly increases with the voltage until for about 1 volt between the plates the positive and negative currents are nearly equal. The curve for carbonic acid with a positive charge on the uranium is also shown. It will be seen that the initial slope of the curve is greater for carbonic acid than for hydrogen

It is remarkable that the current with zero E.M.F. for hydrogen is about two–thirds of its value when 216 volts are acting between the plates. The ions in hydrogen diffuse more rapidly than in air, and in consequence a large proportion of the negative ions reach the uranium and give up their charge to it before recombination can take place.

If the radiation fell between two plates of exactly the same metal, the inequality between the positive and negative current values for low voltages would almost disappear, but even in that case there would still be an apparent current through the gas due to the fact that the negative carriers diffuse with greater rapidity than the positive. Effects of this kind have been studied for Röntgen radiation by Zeleny[24].

[24]Phil. Mag., July 1898

For large E.M.F.'s no appreciable difference in the value of the current could be detected whether the uranium was positively or negatively charged, i.e., positive and negative electrifications are discharged with equal facility.

For the different gases the current tends more rapidly to a saturation value in hydrogen than in air, and more rapidly in air than in carbonic acid. In all these cases there is still a slight increase of current with increase of E.M.F. long after the "knee" of the saturation curve has been passed, and in no case has complete saturation been observed at atmospheric pressure, even for a potential gradient of 1300 volts per cm.

The explanation of the general form of the curves showing the relation between current and electromotive force for ionized gases has been given in a previous paper.[25] In the case of uranium conduction the phenomenon is still further complicated by the want of uniformity of ionization between the plates and the resulting disturbance of the electrostatic field due to the excess of ions of one kind between the plates.

The ionization of the gas is greatest near the uranium surface, and falls off rapidly with the distance. The rate of recombination of the ions thus varies from point to point between the plates, being greatest near the surface of the uranium.

The equations which express completely the relation between the current and electromotive force for the rate of leak between two parallel plates, one of which is covered with uranium, are very complex and cannot be expressed in simple form. The disturbance of the electrostatic field between the plates, due to the movement of the ions, has to be considered as well as the variable rates of recombination at the different points, and the difference of velocity between the positive and negative ions.

The great difficulty in producing complete saturation, i. e. to reach a stage when all the ions produced reach the electrodes, may be due to one or more of three causes: –

(1) Rapid rate of recombination of the ions very near the surface of the uranium.

(2) Presence of very slow moving ions together with the more rapidly moving carriers.

(3) An effect of the electric field on the production of tho ions.

The effect of (3) is probably very small, for there is no experimental evidence of any such action unless the electromotive forces are very high.

[25] J.J. Thomson and E. Rutherford, Phil. Mag. November 1896

That the slow increase of the current in strong fields is due to (1) rather than (2) receives some support from an experiment that has been recently tried. Instead of measuring the current with the uranium covering one electrode, the air which had passed over uranium was forced between two concentric cylinders between which the electromotive force was acting. The rate of leak was found to only increase 2 or 3 per cent. when the E.M.F. was increased from 16 to 320 volts. This increase is much smaller than in the results previously given. Since the effect of (2) would be present in both cases, this experiment seems to show that the difficulty in removing all the ions from the gas is not due to the presence of some very slow–moving carriers.

Some current electromotive–force curves for small voltages have been obtained at different pressures. Examples of the results are shown in fig. 15, which gives the relation between the current and the electromotive force at pressures of 760, 380, 190, and 95 mm. of mercury.

These results were obtained with a different apparatus and by a different method to that given in fig. 12. Two parallel insulated metal plates, about 3 cm. apart, one of which was covered with uranium oxide, were placed inside an air–tight vessel. One plate was connected to earth and the other to the electrometer. The plate connected to the electrometer was then charged up to a potential of 10 volts. On account of the presence of the uranium oxide the charge slowly leaked away, and the rate of movement of the electrometer–needle measured the current corresponding to different values of the electromotive force.

The method did not admit of the accuracy of that previously employed (see fig. 12). The rate of leak for small factions of a volt could not be determined, so that in the curves fig. 15 it is assumed that the current was zero when the electromotive force was zero. This is probably not quite accurate owing to the slight contact–difference of potential between the plates, so that there was a small initial current for zero external electromotive force.

The general results show that the gas tends to become more readily saturated with diminution of pressure. The variation of the current with the E.M.F. depends on two factors — the velocities of the ions, and their rate of recombination. Some experiments on the velocity of the carriers[26]. in ultra–violet light conduction showed t hat the velocity of the ions in a given electric field is inversely proportional to the pressure. This is probably also true for the ions in Röntgen conduction; so that under the pressure of 95 mm. the ions would move eight times as fast as at atmospheric pressure. The variation of the rate of recombination with pressure has not yet been

[26]Proc. Camb. Phil. Soc. Feb. 21, 1888

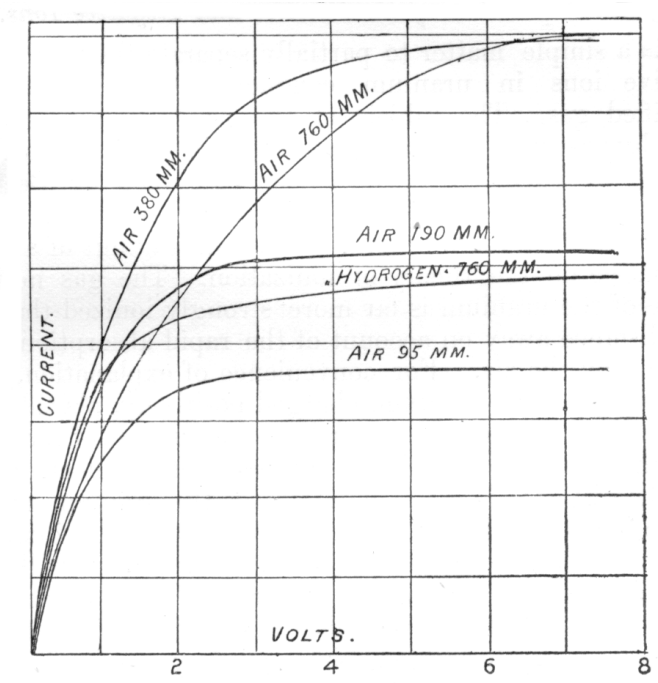
AIR 380 MM.
AIR 760 MM.
AIR 190 MM.
HYDROGEN. 760 MM.
AIR 95 MM.
CURRENT.
VOLTS.
2
4
6
8

Figure 15:

determined.

The curve for hydrogen at atmospheric pressure is also given in fig. 15, and shows that hydrogen is about as easily saturated as air at 190 mm. pressure.

§ 17 *Separation of the Positive and Negative Ions.*

It is a simple matter to partially separate the positive and negative ions in uranium conductions and produce an electrified gas. The subject of the production of electrification by passing a current of air over the surface of uranium enclosed in a metal vessel has been examined by Beattie,[27] who found the electrification obtained was of the same sign as the charge on the uranium. His results admit of a simple explanation on the theory of ionization. The gas near the surface of the uranium is far more strongly ionized than that some distance away on account of the rapid absorption of the radiation by the air. For convenience of explanation, let us suppose a piece of uranium, charged positively, placed inside a metal vessel connected to earth, and a current of air passed through the vessel. Under the influence of the electromotive force the negative ions travel in towards the uranium, and the positive ions towards the outer vessel. Since the ionization is greater near the surface of the uranium, there will be an excess of positive ions in the air some distance away from the uranium. Part of this is blown out by the current of air, and gives up its charge to a filter of cotton–wool. The total number of negative ions blown out in the same time is much less, as the electromotive intensity, and therefore the velocity of the carrier, is greater near the uranium than near the outside cylinder. Consequently there is an excess of positive ions blown out, and a positively electrified gas is obtained. As the potential difference between the electrodes is increased, the amount of electrification obtained depends on two opposing actions. The velocity of the carriers is increased, and consequently tho ratio of the number of carriers removed is diminished. But if the gas is not saturated, with increase of electromotive force the number of ions travelling between the electrodes is increased, and for small voltages this increase more than counterbalances the diminution due to increase of velocity. The amount of electrification obtained will therefore increase at first with increase of voltage, reach a maximum, and then diminish; for when the gas is saturated no more ions

[27] Phil. Mag. July 1897, XLIV. p. 102.

can be .supplied with increase of electromotive force. This is exactly the result which Beattie obtained, and which I also obtained in the case of the separation of the ions of Röntgenized air. The fact that more positive than negative electrification is obtained is due to the greater velocity with which the negative ion travels. (See § 14.)

The properties of this electrified gas are similar to that which has been found from Röntgen conduction. The opposite sign of the electrification obtained by Beattie for uranium induction, and by myself for Röntgen conduction[28] is to be expected on account of the different methods employed. For obtained electrification from Röntgenized air a rapid current of air was directed close to the charged wire. In that case the sign of the electrification obtained is opposite to that of the wire, as it is the carriers of opposite sign to the wire which are blown out before they reach the wire. In the case of uranium the current of air filled the cross–section of the space between tho electrodes; and it has been shown that under such conditions electrification of the same sign as the uranium is to be expected.

§ 18 *Discharging–powder if Fine Gauzes.*

Air blown over the surface of uranium loses all trace of conductivity after being forced through cotton–wool or through any finely divided substance. In this respect it is quite similar to Röntgenized air. The discharging–power of cotton–wool and fine gauzes is at first sight surprising, for there is considerable evidence that the ions themselves are of molecular dimensions, and might therefore be expected to pass through small orifices; but a little consideration shows that the ions, like the molecules, are continually in rapid motion, and, in addition, have free charges, so that whenever they approach within a certain distance of a solid body they tend to be attracted towards it, and give up their charge or adhere to the surface. On account of the rapidity of diffusion[29] of the ions, the discharging–power of a metal gauze, with openings very large compared with the diameter of a carrier, may be considerable. The table below gives some results obtained for the discharging–power of fine copper gauzes. The copper gauze had two strands per millim., and the area occupied by the metal was roughly equal to the area of the openings. The gauzes filled the cross–section of the tube at A (fig. 9), and were tightly pressed together. The conductivity of the air was

[28] Phil. Mag. April 1897.
[29] Townsend, Phil. Mag. June 1898.

tested after its passage through the gauzes, the velocity of the air along the tube being kept approximately constant. The rates of leak per minute due to the air after its passage through different numbers of gauzes is given below.

Number of Gauzes	Rate of leak in divisions per minute
0	44
1	32.5
2	26.5
3	19.5
4	10.5
5	6

After passing through 5 gauzes the conductivity of the air has fallen to less than $^1/_7$ of its original value. Experiments were tried with gauzes of different degrees of coarseness with the same general result. The discharging–power varies with the coarseness of the gauze, and appears to depend more on the ratio of the area of metal to the area of the openings than on the actual size of the opening. If a copper gauze has such a power of removing the carriers from the gas, we can readily see why a small plug of cotton–wool should completely abstract the ions from the gas passing through it. The rapid loss of conductivity is thus due to the smallness of the carrier and the consequent rapidity of diffusion.

§ 18 *General Remarks.*

The cause and origin of the radiation continuously emitted by uranium and its salts still remain a mystery. All the results that have been obtained point to the conclusion that uranium gives out types of radiation which, as regards their effect on gases, are similar to Röntgen rays and the secondary radiation emitted by metals when Röntgen rays fall upon them. If there is

no polarization or refraction the similarity is complete. J.J. Thomson[30] has suggested that the regrouping of the constituents of the atom may give rise to electrical effects such as are produced in the ionization of a gas. Röntgen[31] and Wiedemann's[32] results seem to show that in the process of ionization a radiation is emitted which has similar properties to easily absorbed Röntgen radiation. The energy spent in producing uranium radiation is probably extremely small, so that thee radiation could continue for long intervals of time without much diminution of internal energy of the uranium. The effect of the temperature of the uranium on the amount of radiation given out has been tried. An arrangement similar to that described in § 11 employed. The radiation was completely absorbed in the gas. The vessel was heated up to about 200° C.; but not much difference in the rate of discharge was observed. The results of such experiments are very difficult to interpret, as the variation of ionization with temperature is not known.

I have been unable to observe the presence of any secondary radiation produced when uranium radiation falls on a metal. Such a radiation is probably produced, but its effects are too small for measurement.

In conclusion, I desire to express my best thanks to Prof. J.J. Thomson for his kindly interest and encouragement during the course of this investigation.

Cavendish Laboratory, Sept. 1st, 1898.

[30] Proc. Camb. Phil. Soc. vol. IX. pt. VIII. p. 397 (1898).
[31] Wied. Ann. LXIV. (1898).
[32] Zeit. f. Electrochemie, II. p. 159 (1895)