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II. *Energy of Röntgen and Becquerel Rays, and the Energy required to produce an Ion in Gases.*

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The primary object of the investigations described in this paper was the determination of the amount of energy required to produce a gaseous ion when Röntgen rays pass through a gas, and to deduce from it the energy of the radiation emitted per second by uranium, thorium, and other radio-active substances. In order to determine the "ionic energy" (as it will be termed for brevity), it has been necessary to make a special investigation to measure accurately the heating effect of X rays when the rays are absorbed in metals, and also the absorption of the rays in gases.

The method employed to determine the ionic energy was briefly as follows :—The total energy of the rays emitted per second was determined by measuring the heating effect of a known proportion of the rays when absorbed in a metal. The total number of ions produced by complete absorption of the rays in the gas was deduced from measurements on the current produced by the ionization of a known volume of the gas and of the absorption of the rays in the gas, assuming the value of the ionic charge recently determined by J. J. Thomson.

On the assumption that all the energy of the X rays is absorbed in producing ions in the gas, the total energy of the rays, divided by the total number of ions produced, is a measure of the energy required to produce an ion.

In the course of the investigation the following subjects have been considered :—

(1.) Measurement of the heating effect of X rays and the total energy of the rays emitted per second.

(2.) Efficiency of a fluorescent screen excited by X rays as a source of light.

(3.) Absorption of X rays in gases at different pressures.

(4.) Energy required to produce an ion in gases, with deductions on—

  (*a.*) Distance apart of the charges of ions in a molecule.

  (*b.*) Minimum potential required to produce a spark in the gases.

(5.) Rate of emission of energy from the radio-active substances, uranium, thorium, radium, and polonium.

Heating Effect of X Rays.

Experiments on the heating effect of Röntgen radiation have been made by Dorn.* The rays were partly absorbed in metal foil placed in one bulb of a differential air-thermometer. The heat absorbed by the metal was communicated to the gas and the resulting change of volume observed. In order to obtain a measure of the heat supplied, the heating effect due to a current in a wire placed inside the bulb was observed.

Moffat† has deduced the energy of X rays from photometric comparisons of a fluorescent screen with the Hefner amyl lamp, *assuming* the efficiency of a fluorescent screen excited by X rays as a source of light. Knowing the value of the energy of the visible light of the Hefner standard, the heating effect of the rays can be deduced.

In determining the heating effect of the rays, difficulties arise from which measurements of the heating effect of weak sources of visible light are free. In the first case, the inconstancy of an X-ray bulb as a source of radiation for measurements extending over long intervals is always a cause of trouble. In the second place, the X rays are only slightly absorbed in thin metal foil, while light rays are completely absorbed at the surface of thin metal coated with lampblack. Only a small portion of the energy of the rays is absorbed in passing through thin metal foil, and in consequence a bolometer like Langley's, where the change of resistance of a very thin metal sheet, due to heat supplied by the rays, is observed, is not very suitable for measurements on the energy of X rays. Ordinary thermopiles are open to grave objections, as will be explained later in this paper.

In order to measure the heating effect of the rays, a specially designed platinum bolometer was employed, and the heating effect was determined from the change of resistance of the platinum.

Description of Bolometer. (Fig. 1.)

A platinum strip, about 3 metres long, ·5 centim. wide, and ·003 centim. thick, was wound on an open mica frame made as light as was compatible with rigidity. The frame was 10 centims. square, and of a shape shown in fig. 1 (*a*). The platinum strip was wound round and round the frame, the strips on the front of the frame partly overlapping the corresponding ones at the back, but not touching them. The platinum strip (fifteen complete turns in all) was held in position by notches in the side of the mica frame, and the distance between each turn of the strip was 1 millim.

* 'Wied. Annal.,' vol. 63, p. 150.

† 'Roy. Soc. Edin. Proc.,' 1898.

Two of these grids were constructed as similar as possible, and mounted in the same vertical plane on a wooden base.

Resistance of each grid = 4·2 ohms.

Area of platinum surface of grid = 92·2 sq. centims.

Fig. 1(*a*).

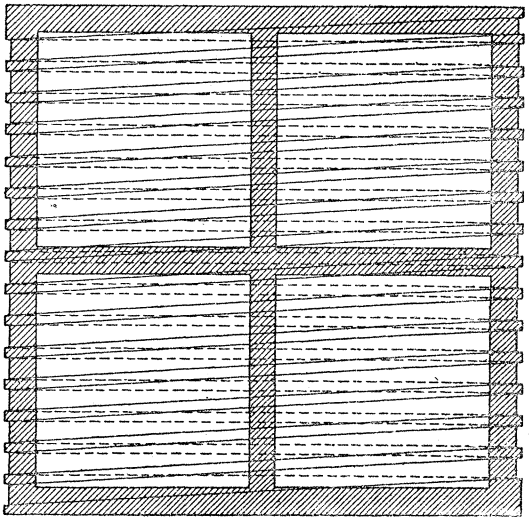
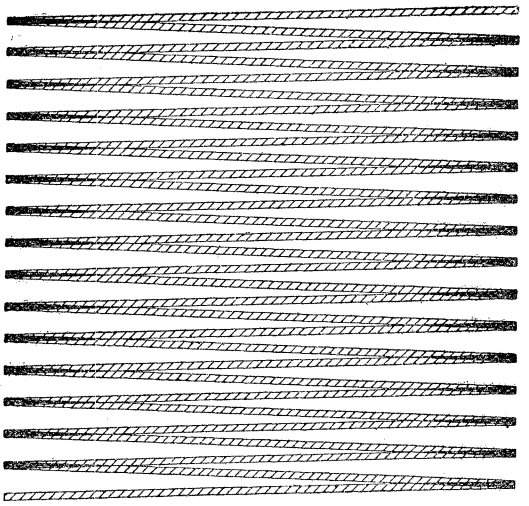


Fig. 1(*b*).



The X rays incident on the grid for the most part passed through two thicknesses of platinum, but, on account of the windings not completely overlapping, the rays in some portions passed through one thickness only. This was clearly shown in an X-ray photograph of the grid, which is sketched in fig. 1 (*b*), where the shaded portions are the areas where the rays only passed through one thickness of the platinum.

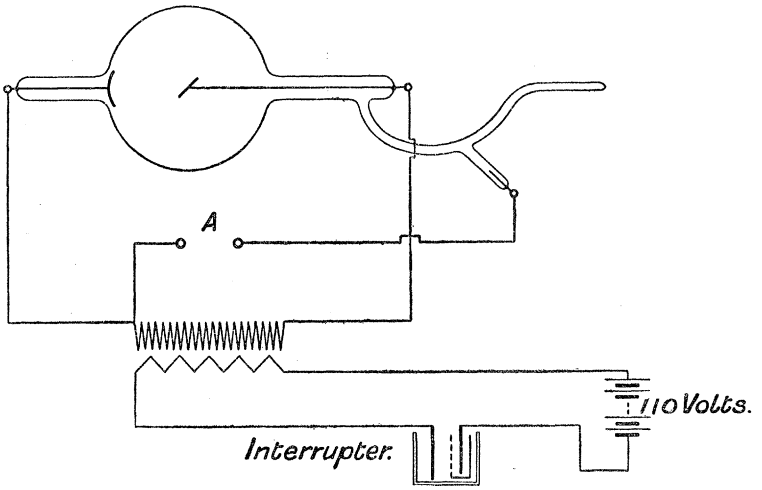
The absorption of the rays in the mica frame was very slight, and it was only on very careful inspection of the photograph that the outline of the frame could be observed. For the X rays employed, the intensity was cut down to ·45 of its value after passing through the grid.

Focus Tube.

The rays were excited in an automatic focus tube of the pattern shown in fig. 2, with a platinum anode and an aluminium cathode. The tube was excited by a large coil, using a Wehnelt interrupter on a 110-volt circuit. The alternative spark gap A was always kept the same length—about 5 inches. The bulb was a very hard one, and there was generally a fairly rapid succession of sparks across A during the working of the bulb in order to keep the vacuum constant. The constancy of the length of the spark A is of great importance in these experiments, in order to obtain rays of the same degree of penetration. A diminution of the spark length lowers the vacuum of the gas in the tube and produces rays of lower penetrating power.

After working the coil for 10 seconds, the platinum plate became red-hot and remained fairly constant during the next 30 seconds. It was generally found advisable to run the bulb at intervals for a quarter of an hour before beginning measurements, in order to get it into a steady state for the emission of rays of constant intensity. Under these conditions experiments could be made from day day with a maximum variation of intensity of 30 per cent., and generally with much less.

Fig. 2.



The bulb employed gave out rays of great intensity and great penetrating power. A fluorescent screen was brightly lighted at a distance of 20 feet from the bulb. With a "soft" tube and less intense rays, it would have been difficult to measure the heating effect with accuracy.

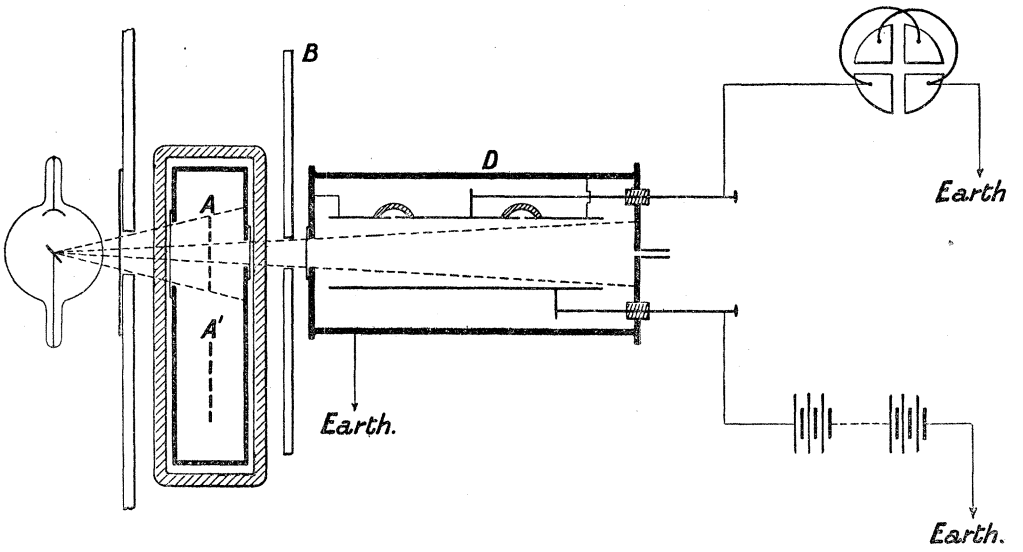
Wehnelt Interrupter.

The Wehnelt interrupter was of a simple pattern. One lead plate was placed inside a thick glass vessel (a Leclanché cell was used) with three holes about 1 millim. in diameter bored in one side. The glass vessel was placed inside an ebonite box with a lead electrode, and was filled with dilute sulphuric acid in the usual manner The acid was kept cool by having a water circulation through a coil of lead pipe in the ebonite box. By suitably tapering the holes in the glass the interrupter was made to work steadily at a slow speed and gave strong discharges in the coil. The E.M.F. employed was 110 volts and the current was about 15 amperes. The average number of breaks per second was 57. In the course of more than six months' work the glass vessel was only replaced once, on account of the gradual increase of the diameter of the holes.

Arrangement of Apparatus.

Fig. 3 shows the general arrangement of the experiment. The bulb and coil were completely enclosed in a small lead-covered room connected to earth. The rays passing through a circular hole in the lead, covered with aluminium, fell on one of the platinum grids A. A pencil of the rays, after traversing the grid, passed through a rectangular hole in the thick lead plate B, and made the air a partial conductor inside the discharge cylinder D. The vessel D merely served as a means of testing the constancy of the rays given out by the bulb by noting the current produced between the charged electrodes. The discharge apparatus will be described in detail later.

Fig. 3.



The two grids A and A′ formed two arms of a Wheatstone bridge (fig. 4). The other two arms were formed by a manganin cylinder potentiometer of 22 ohms, corresponding to a length of about 25 metres of wire. A sensitive low-resistance galvanometer was employed, and the deflection read with a telescope and scale.

The balance was first obtained for a momentary passage of the battery current. The rays were then turned on for a given time, generally either 30 or 45 seconds. The rays falling on the grid A were partly absorbed and heated the platinum to a slight extent, and the resistance consequently changed. The deflection from zero was noted immediately after the cessation of the rays.

In order to obtain a measure of the heating effect, a steady current was sent through the grid A for the same time as the rays acted. The magnitude of this current was adjusted until the deflection from zero was the same as for the rays.

When this is the case, the amount of heat, H, supplied per second by the rays is equal to the amount of heat generated by the current:

$$H = \cdot 24\, i^2\, R \text{ gramme calories},$$

where i = current through the grid,
and R = resistance of the grid.

The heating effect due to the rays was small and consequently care had to be taken to avoid disturbances of the balance due to outside causes. The grids were enclosed in a lead vessel with an aluminium window in front of the grid A. A thick covering of felt completely enclosed the lead vessel. Between the bulb and the grid there was one plate of aluminium 1 millim. thick and two sheets of thin aluminium, besides the felt covering. A lead screen in addition could be placed over the hole H. When the hole was covered thus with the lead plate, there was no disturbance of the zero, showing that the rays falling on the grid were responsible for the heating effect and the rays alone.

In practice it was found necessary to remove the sensitive astatic galvanometer employed a considerable distance away from the induction coil before the magnetic disturbances due to it were negligible. This necessitated additional leads, and in consequence more troublesome changes of the balance. For the most part, however, the changes of the balance point were gradual and, if necessary, could be accurately allowed for during the short time the grid was exposed to the rays.

Two observers were required, one to start and stop the rays and to note the electrometer deflections, and the other to observe the galvanometer deflections. With the aid of a simple system of signals, the experiments presented no serious difficulty.

In order that the rays should be, as far as possible, of constant intensity when falling on the grid, the hole in the lead plate between the bulb and the grid was covered with a lead screen, operated from a distance, during the first 15 seconds after the rays were turned on. By means of a cord the screen was suddenly removed and the rays stopped after a definite time by breaking the current.

The following table is an example of a succession of observations extending over several hours:—

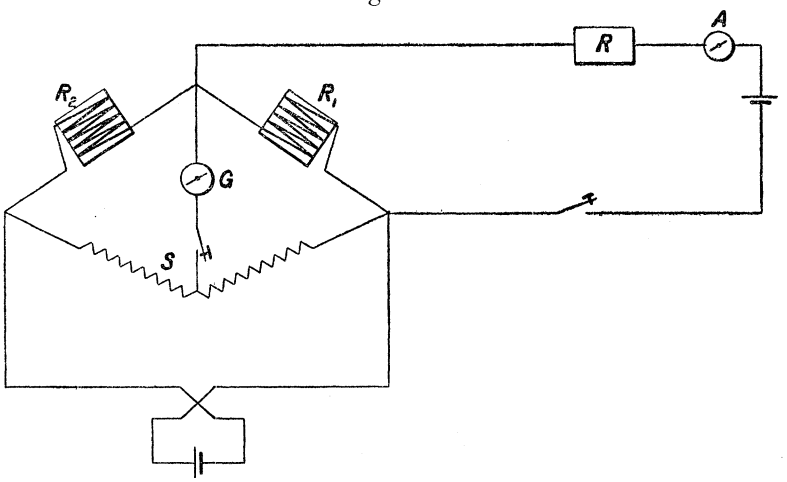
Time of exposure to the rays = 30 seconds.
Testing current through the grids = ·04 ampere.

Deflection of galvanometer in millims.	Deflection of electrometer in scale divisions per second.
17·0	5·17
18·6	5·53
18·4	5·33
17·8	5·27
Mean value = 17·9.	Mean deflection = 5·32

In order to measure the amount of heat corresponding to this deflection of the galvanometer, a steady current from a separate battery was passed through the grid previously exposed to the rays and for the same time.

Fig. 4 shows the connections. As it was necessary to determine the change of zero *immediately after* the passage of the current for a definite time, the arms of the bridge were undisturbed, and consequently a portion of the heating current passed through the grid R_2.

Fig. 4.



Resistance of grid R_1 exposed to rays = 4·2 ohms.
,, second grid R_2 = 4·28 ohms.
Total resistance of the other two arms and leads, S = 23·04 ohms.

If i be the current from the battery supplied for heating purposes then,

Current through R_1 = ·867 i.
,, ,, R_2 = ·133 i.
Heating effect on R_1 = ·752 i^2 gramme calories.
,, ,, R_2 = ·018 i^2 ,,
Difference in amount of heat supplied to R_1 and R_2 = ·734 i^2.

We thus see that most of the heating effect is confined to the grid R_1.

From a special series of experiments it was found that the deflection from zero of the galvanometer in a given time due to the heating by the current was very closely proportional to the square of the current. It was therefore not necessary to find experimentally the exact value of the current to give the same deflection as the rays, but from observations on one known current the results could be obtained by interpolation.

It was found that under the same conditions as the table given above, a current i = ·0200 ampere gave a mean deflection from zero in 30 seconds of 37·4 divisions. The mean deflection due to the rays was 17·9 divisions.

Thus the amount of heat supplied to the grid per second by the rays

$$= \frac{17{\cdot}9}{37{\cdot}4} \times ({\cdot}02)^2 \times {\cdot}734 = {\cdot}000141 \text{ gramme calorie.}$$

In the first stage of the investigation a null method was employed to measure the heat of the rays, but unexpected difficulties arose, and the method was abandoned. The battery current was kept steadily flowing through the grids, and the balance obtained. During the time the rays were on, a portion of the current through the grid was shunted through a resistance of known value. The value of the shunt resistance was adjusted until there was no change of the balance immediately after the rays were stopped and the shunt circuit broken.

It was difficult, however, to obtain satisfactory results, partly on account of the inconstancy of the rays, but chiefly on account of the slight difference of heating effect of the two grids for equal currents. The strength of current through the grid was generally ·04 of an ampere, and with this current the inequality of the grids was immediately seen by a change of balance, when the current was applied for some time. The addition of a shunt to one grid caused a variation of current through both grids, and the change of temperature, due to inequality of the grids, introduced an error which was not negligible compared with the small heating effect of the rays. The method was not so rapid or certain a the one finally employed.

Measurement of Heating Effect by Thermopile.

Some experiments were made to see it a thermopile was suitable for a measure of the heating effect of X rays. The only thermopiles in the laboratory were of the ordinary solid type of 65 bismuth antimony couples. The thermopile was placed inside a metal tube covered with aluminium at one end and a rock-salt plate at the other. With a sensitive low-resistance galvanometer a deflection of 15 millims. could be obtained in 30 seconds. The rate of supply of heat was standardised by using a standard Hefner amyl-acetate lamp, the total radiation from which has been determined in absolute measure by Tumlirz.* It was observed that the thermopile, when exposed to the X rays, took up its final temperature very much more slowly than when exposed to the radiation from the lamp, and that the results obtained differed considerably from the bolometer method. The cause of the discrepancy lies in the unsuitability of a solid thermopile for measurements on X rays. The radiation from the lamp falling on the lampblack coating of the thermopile is absorbed at the surface of the metal, while the X rays penetrate a distance of the order of 1 millim. before much of the energy is absorbed. On account of this, the maximum rise of temperature near the surface of the junction on which the E.M.F. depends is less

* 'Wied. Annal.,' vol. 38, p. 640.

with X rays than with light for equal intensities of radiation. The deflection of the galvanometer is thus less for X rays than for light-waves of equal energy.

From these considerations it is obvious that the solid type of thermopile is most unsuitable for such work; but a modified thermopile of thin plane sheets of metal, *e.g.*, iron and constantin, would probably give better results and be simpler to manipulate than the bolometer. With thin sheets the heat would be equally distributed over the cross-section due to diffusion, and no appreciable error would arise. The method, however, has the objection that the amount of heat must be standardised by a known lamp or source of radiant energy.

Total Energy of the Rays emitted per Second.

When X rays fall on a metal plate, the plate is heated, and the question at once arises whether we are justified in assuming that the energy of the rays stopped by the metal plate is transformed into heat in the plate. The experiments of Perrin, Sagnac, and J. J. Thomson have clearly shown that when X rays strike a solid body, secondary rays are set up which ionize the gas and act on a photographic plate. These secondary rays are of a far less penetrating character than the rays that excited them; but on account of the ease with which they are absorbed in the gas, the amount of ionization per cub. centim. in the gas near the surface of the body may be greater than that due to the direct rays. The total number of ions produced by the scattered rays depends to a great extent on the density of the metal as well as on the intensity of the incident rays. The total number of ions produced by complete absorption of the scattered rays is generally only a small proportion of the number produced by complete absorption of the direct rays. Assuming that an ion in both cases requires the same expenditure of energy to produce it, the energy of the scattered rays is thus only a small proportion of the total energy of the incident rays.

The secondary rays are set up both at the points of incidence and emergence of the rays falling on the grid. The heating effect on the grid is thus less than the heat equivalent of the energy of the rays stopped by the grid by the portion of the energy used up in exciting secondary rays. The correction is probably small, and has been neglected in these experiments, but it is hoped in a future investigation to determine its value.

There is no evidence that the chemical energy of platinum is in any way altered by the passage of the rays through it, and, as far as our present knowledge goes, the energy of the rays stopped minus the energy of the scattered radiation, is transformed into heat within the platinum.

In a case where there is a chemical change, *e.g.*, when the rays fall on a photographic film, the heating effect would not be the equivalent of the energy absorbed.

It has been shown by Röntgen and other observers that the intensity of the rays given out from the front surface of a platinum plate of a focus tube is approximately

equal in all directions. In the experiment the rays fell normally on the centre of the grid, but on account of the size of the grid, the intensity of the rays could not be considered constant over its surface. The intensity of the rays diminishes, and the obliquity of the angle of incidence increases from the centre of the grid outwards. In consequence of this, a greater proportion of the incident radiation is absorbed at the edges than at the centre.

The intensity of the rays was cut down to about ·45 of its incident value in passing normally through the grid. It can be shown, by approximate integration over the surface of the grid, that for the distance of the grid from the source of the rays, namely, 26 centims., and the dimensions of the grid, the actual energy absorbed is about 2 per cent. less than if the rays had the same intensity over the surface of the grid as at the centre, and had fallen normally at all points of the grid.

For the special bulb employed, it was shown that the rate of supply of heat to the grid was equal to

$$\cdot 00014 \text{ gramme calorie per second.}$$

This corresponded to a maximum rise of temperature of about 1/200° C.

Distance of the centre of the grid from the source of the rays = 26 centims.

Area of grid = 92·2 sq. centims.

Now ·55 of the incident radiation was absorbed in the grid.

Total energy of the rays falling on the grid is approximately

$$= \cdot 00025 \text{ gramme calorie per second.}$$

Therefore the total heating effect due to all the rays emitted from the front of the plate (omitting absorption in the glass, air, and screens)

$$= \frac{2\pi \times (26)^2}{92 \cdot 2} \times \cdot 98 \times \cdot 00025 = \cdot 011 \text{ gramme calorie per second,}$$

$$\text{or } \cdot 046 \text{ watt.}$$

Now the number of discharges per second in the bulb was 57, and Trouton* has shown that the duration of the rays during each discharge of an induction coil is less than 10^{-3} second, and probably about 10^{-4} second. Assuming the average duration of the rays for each discharge is 10^{-4} second, the rate of emission of energy while it lasts

$$= 1 \cdot 95 \text{ gramme calorie per second.}$$

The heating effect of the sun's rays falling normally on 1 sq. centim. surface is about

$$= \cdot 035 \text{ gramme calorie per second.}$$

The maximum rate of emission of energy as X rays from the bulb is thus about 56 times greater than the amount of energy per sq. centim. due to the sun's rays.

* 'Brit. Assoc. Report,' 1896.

Efficiency of a Fluorescent Screen as a Source of Light.

Experiments were made to determine the efficiency of a fluorescent screen as a transformer of Röntgen radiation into visible light.

Photometric observations of the light emitted by a fluorescent screen, excited by X rays, have been made by A. MOFFAT,* who deduced the energy of the rays, by assuming that the coefficient of transformation of the energy into visible light was 4 per cent., the value found by E. WIEDEMANN† for the transformation of radiant energy into luminescence.

It was not the object of this investigation to make a complete photometric comparison, but to deduce an approximate coefficient of transformation for a definite experimental arrangement which could readily be reproduced in practice. For this purpose a piece of fluorescent screen was placed over one of the diffusive surfaces of a Lummer-Brodhun screen, and the diffused light of the screen compared with the diffused light of the amyl lamp in the usual manner. The ratio of the square of the distance of the screen from the bulb to the square of the distance of the lamp was taken as the ratio of the intensities of the light emitted by the X-ray bulb and lamp. In this case the amount of the light of the amyl lamp absorbed in the plaster of Paris surface was neglected.

Dr. E. SUMPNER‡ has shown that a piece of blotting-paper reflected over 80 per cent. of the light incident upon it, and it was found experimentally that the plaster of Paris surface of the screen was a still better reflector.

The current in the discharge vessel was determined, during the measurements of the energy, in absolute measure, and also during the comparison of the screen with the amyl lamp, in order to correct for changes of intensity of the rays during the observations. In this way it was found, using a platino-barium cyanide screen, that

$$\frac{\text{Intensity of light from fluorescent screen}}{\text{Intensity of light from amyl lamp}} = \cdot 0206.$$

Now if the intensity, I, of the visible light from a Hefner amyl lamp is given by

$$I = K/r^2$$

from the experiment of TUMLIRZ§ the value of K for the visible light is equal to

$$\cdot 00361 \text{ gramme calorie per second,}$$

and the total energy radiated by the lamp is 41·1 times the energy of the light radiation alone.

Now in the experiments with the bolometer the heating effect of the rays incident

* 'Roy. Soc. Edinburgh Proc.,' 1898. † 'Wied. Annal.,' vol. 37, p. 233.

‡ 'Phil. Mag.,' February, 1893. § 'Wied. Annal.,' vol. 38, p. 640.

on the grid, area 92·2 sq. centims., at a distance of 26 centims. from the source of rays, for the same strength of rays as those incident on the fluorescent screen, was ·00032 gramme calorie per second.

$I = K/r^2$, and the value of K, which represents the amount of energy due to the rays falling normally on a surface of 1 sq. centim. at a distance of 1 centim. from the source of rays

$$= \cdot0023 \text{ gramme calorie.}$$

The intensity of the X rays was thus ·64 of the intensity of the visible light of the standard Hefner lamp.

Now the efficiency of transformation of X rays into light

$$= \frac{\text{energy radiated as light}}{\text{energy supplied by the rays}} = \frac{\cdot0206 \times \cdot00361}{\cdot73 \times \cdot0023} = \cdot044,$$

since it was found electrically that ·73 of the rays were absorbed in the screen.

The efficiency of transformation is thus

$$4\cdot4 \text{ per cent.}$$

If we assume that 85 per cent. of the incident light is diffused from the surface of the Lummer-Brodhun screen, the efficiency of transformation is about 3·7 per cent.

A calcium tungstate screen, in which the absorption was ·36, gave almost the same efficiency of transformation.

The results we have obtained afford a simple means of expressing the intensity of X rays in absolute measure, assuming the coefficient of transformation of a fluorescent screen to be about 4 per cent.

Two experiments would be necessary—

(1.) The intensity of the light from the screen would be compared with a Hefner standard lamp.

(2.) The absorption of the rays by the screen would be measured electrically or photometrically by placing a portion of the screen to absorb the rays.

Let I_1 and I_2 be the intensities of X rays and a Hefner standard lamp in absolute measure, disregarding absorption of rays in glass, metal screens, air, &c. When there is equality of illumination let r_1 and r_2 be the distances of the source of rays and lamp from the Lummer-Brodhun screen.

Let r_1 and r_3 be the distances for equal illumination when the rays pass through a piece of the screen before falling on the Lummer-Brodhun screen.

Then ρ, the ratio of transmitted to incident rays for the fluorescent screen, is given by

$$\rho = r_2^2/r_3^2.$$

Ratio of incident energy absorbed $= 1 - \rho$.

Therefore it is readily seen that

$$\frac{I_1}{I_2} = \frac{r_1^2}{r_2^2(1 - \rho)} \times \frac{100}{4{\cdot}4},$$

since efficiency is 4·4 per cent.

Thus, since $I_2 = {\cdot}00361$ gramme calorie,

$$\therefore \quad I_1 = {\cdot}082 \frac{r_1^2}{r_2^2(1 - \rho)} \text{ gramme calorie.}$$

Thus two simple photometric comparisons would be required to express the energy of the radiation of any particular bulb in absolute measure.

For penetrating rays the absorption in the cardboard of the screen is negligible, but if necessary it can readily be allowed for.

The chief source of difficulty in the comparison is the difference in colour between the light from the Hefner lamp and a fluorescent screen. The fluorescent light appears a greenish-blue, and the amyl lamp a reddish-yellow, when seen side by side in the telescope of a Lummer-Brodhun screen.

Some experiments were made using a coloured glass to make the sources of light more nearly a match in colour. A greenish coloured glass was found to give a good colour match when interposed between the screen and amyl lamp. On determining by means of a thermopile the amount of the visible energy of the Hefner lamp which was allowed to go through the glass, it was found to be so small (less than 2 per cent.) that a special investigation was required to find the coefficient of transmission with accuracy. The experiments were not continued, owing to lack of time, but the evidence showed that by using a coloured screen in the path of the amyl lamp to give the same tint as the fluorescent screen, the efficiency of the transformation of the screen was much higher in that case than the 4 per cent. obtained by using no coloured glass or solution.

Energy required to produce an Ion.

The method employed to determine the energy required to produce an ion in gases exposed to Röntgen rays depended on the measurement of the heating effect of the rays, and of the total number of ions produced by the radiation in the gas. If H is the number of calories given out per second by the rays, and E the energy in ergs of the rays emitted per second, then

$$E = JH \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1).$$

If W is the average amount of energy required to produce an ion, then

$$nW = E \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2),$$

where n is the number of ions produced per second, supposing that all the energy of the rays, absorbed in the gas, is due alone to the production of ions.

In order to determine the number of ions, n, it is necessary to measure the maximum current that can be produced between two electrodes when all the ions produced by the rays in the gas reach the charged electrodes before there is any appreciable loss of their number due to recombination. If i is the maximum or *saturation* current through the gas, then

$$i = n\epsilon,$$

where ϵ is the charge on an ion.

The value of ϵ has been determined by J. J. Thomson,* and is equal to $6{\cdot}5\ 10^{-10}$ electrostatic unit.

From (1) and (2)

$$nW = JH,$$

therefore

$$W = \frac{JH\epsilon}{i}.$$

In order to determine W it is thus necessary to determine the value of H and i.

The considerations on which the method is based are:

(1.) When the X rays are absorbed by a solid substance, the greater proportion of the energy is given up to the substance in the form of heat.

(2.) The energy of the rays absorbed in passing through a given volume of the gas is used up in producing ions.

(1) has been considered earlier in the paper, and it has been shown that we are probably justified in assuming that a very large proportion of the energy due to rays absorbed in a substance like platinum is transformed into heat. A small proportion of the total energy is used up in setting up secondary rays at the point of incidence of the rays on a solid conductor and also at the point of emergence.

In regard to (2), one of the authors† has previously shown that the absorption of the rays in a gas is roughly proportional to the intensity of the ionization in the gas. Gases and vapours, which are made good conductors by the rays, also strongly absorb them. The absorption of the rays in the gas has no direct connection with the molecular weight or density of the gas. For example, in hydrochloric acid gas the rays are far more readily absorbed than in carbonic acid, a gas of greater density.

Perrin has shown that the ionization of a gas is approximately proportional to the pressure. This result has been confirmed by us, and the authors have also found that the absorption of the rays varies directly as the pressure, *i.e.*, as the ionization of the gas. These results point to the conclusion that the absorption of the rays in a gas is closely connected with the number of ions produced. It is possible that there is a certain amount of scattering of the rays in passing through a gas, but if the apparent absorption of the rays were due in any great measure to scattering, we

* 'Phil. Mag.,' Dec., 1898.

† Rutherford, 'Phil. Mag.,' April, 1897.

should expect the absorption to depend chiefly on the density of the gas, and such is not the case. RÖNTGEN and others have observed that the gas itself which has been acted on by the rays gives out a radiation which is able to light up a fluorescent screen. This radiation may be due either to the scattering of the rays, or to the radiation caused by the recombination of the ions. In either case it is probable that the radiation is of a type similar to the secondary radiation set up at the surface of metals when X rays impinge upon them. This secondary radiation is far more readily absorbed in gases than the primary radiation, and would be absorbed in producing ions in the gas. The rate of discharge would be increased, and provided all the scattered, or secondary, radiation were used up in producing fresh ions between the electrodes, no correction for the amount of scattered radiation would be required. This of course proceeds on the assumption that the ions produced by the primary and secondary radiation are the same, and require the same amount of energy in each case to produce them.

It is not practicable to measure directly the total maximum current through the gas, due to the passage of all the ions produced between charged electrodes, as the rays could pass through several hundred metres of the gas before approximately complete absorption took place.

In practice the number of ions produced in a known small volume of the gas is determined, and also the coefficient of absorption of the rays by the gas. The total number of ions that would be produced, provided all the rays were absorbed, can be directly calculated.

An account will now be given of the experiments performed to measure the absorption of the rays in gases.

Absorption of the Rays in Gases.

The bulb employed gave out rays of great intensity and penetrating power, and the absorption of the rays in air was small. About 3 per cent. of the rays were absorbed in passing through a metre of air at atmospheric pressure and temperature. In order to measure the absorption, a delicate null method was employed. No direct method can be employed on account of the smallness of the absorption and the variation of the intensity of the rays during the experiments.

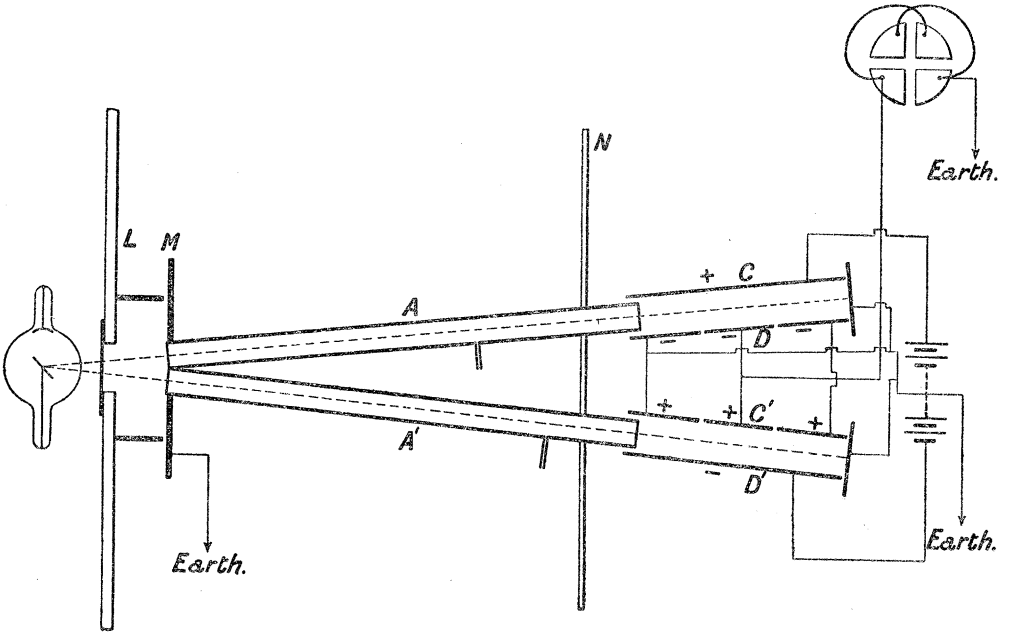
Fig. 5 shows the general arrangement of the apparatus. A similar method was employed by one of us* on a previous occasion to measure the absorption of the rays in gases.

Two long brass tubes, A, A′, 118 centims. long and 3·4 centims. in diameter, were placed horizontally at a slight angle to each other, and in such a position with regard to the bulb that the axes of the two tubes met at a point on the surface of the platinum plate of the anticathode. The ends of the tubes were covered with

* E. RUTHERFORD, 'Phil. Mag.,' April, 1897.

aluminium caps 1 millim. in thickness, and were made air-tight and capable of standing a pressure of 3 atmospheres. The rates of discharge due to the rays after passing through the tubes, were taken between two sets of parallel plates, CD and C′ D′. The plates D and C′ were of the same size and cut into three portions, of which the

Fig. 5.



centre plates were carefully insulated. The centre plates were thus surrounded by a guard ring, and the rates of discharge to the centre plates alone were measured. The centre plates, D and C′, were connected together, and to one pair of quadrants of the electrometer, the other pair of quadrants being connected to earth. The plates, C and D′, were connected to the terminals of a battery of small storage cells of 310 volts, *the middle point of which was to earth.* The electrometer will show no deflection if the intensity of the rays between C and D is exactly equal to the intensity between C′ and D′, since the current between C and D is equal and opposite to the current between C′ and D′.

Lead screens, L, M and N, were placed at the positions marked in the figure, in order to prevent any stray radiation from reaching the testing plates. The wires leading to the electrometer were enclosed in metal tubes, which were connected to earth in order to avoid any loss of charge due to stray radiation or disturbances by any electrostatic field. The electrometer was completely surrounded by a wire gauze The separation of the quadrants of the electrometer was operated from a distance by means of suitable keys. Such precautions are very necessary during the very dry Canadian winter, when the slightest movement causes frictional electrification. The table and the woodwork on which the apparatus was placed was covered over with metal, to prevent the collection of charges either from frictional electrification or the action of the rays near charged conductors.

The tubes were first adjusted so that the rays caused no movement of the electrometer needle. The tube, A, was then rapidly exhausted by means of a Fleuss pump. The intensity of the rays after emerging from the tube was thus greater than for the tube A′ on account of the less absorption, and the electrometer therefore showed a deflection. If the tube A′ were exhausted and the tube A filled with air, the electrometer gave a deflection in the opposite direction. If the end of one of the tubes was closed with a thick lead plate so that no rays could get through, then the rate of movement of the electrometer needle corresponded to the intensity, I, of the rays after emergence from the other tube.

If λ is the coefficient of absorption of the rays in the gas, then the intensity of the rays after passing through a distance d of the tube is $e^{-\lambda d}$ of its value if there had been no absorption.

Since the currents between C and D and between C′ and D′ are proportional to the intensities of the radiations between the plates, then

$$\frac{\text{Difference between currents}}{\text{Total current}} = \frac{I - Ie^{-\lambda d}}{I}$$
$$= 1 - e^{-\lambda d}$$
$$= \lambda d, \quad \text{if } \lambda d \text{ is small.}$$

In order to determine λd, we thus require the ratio of the number of divisions per second, given by the electrometer needle from the balance when one of them is exhausted, to the number per second when the end of the tube containing the gas is covered with a thick lead plate.

The following table gives the results for air at pressures in one tube ranging from ·5 of an atmosphere to 3 atmospheres, the other tube being exhausted :—

Difference of pressures in atmospheres.	Number of divisions in 5 secs. with one tube screened.	Deflection from balance in 20 secs.	λd.
·5	—	—	·0187
1	160	21·8	·034
2	169	48·0	·071
3	172	70·0	·102

The above results are the mean values of a series of measurements. The results for ·5 of an atmosphere were obtained at a different time from the others and with a different sensitiveness of the electrometer. The table shows that the absorption of the rays in the gas is approximately proportional to the pressure.

The value of d was 118 centims.

The value of λ for different pressures is thus given by the following table :—

Pressure in atmospheres.	Value of λ.
·5	·000158
1	·000288
2	·00060
3	·00086

The value of λ at atmospheric pressure and temperature obtained for the same bulb after daily use for two months was found to be ·000270. The value of λ at atmospheric pressure and temperature in the calculations is taken as the mean of these two values, and is thus given by

$$\lambda = \cdot 000279.$$

It is probable that the rays were not homogeneous, and the value of λ must be considered as the mean value for the different kinds of rays. On account of the very small absorption of the rays it was difficult to determine with accuracy the absorption for pressures lower than half an atmosphere. The results, however, indicated that the absorption was, roughly, proportional to the pressure for still lower pressures.

The value of λ was determined for carbonic acid gas at normal pressure and temperature. The absorption was 1·59 times that of air, and the value of λ was found to be ·000457. The results were confirmed by varying the pressure of the air in one tube until there was no disturbance of the electrometer zero. The results agreed with the value obtained above, assuming the absorption in air is proportional to the pressure.

We see from the results given above that the radiation is reduced to half its value with no absorption after passing through a length of 24·7 metres of air at ordinary pressure and temperature.

The value of λ for uranium rays* is 1·6, or the absorption is 6000 times as great for uranium rays as for the X rays employed. The value of λ obtained some years ago for a much "softer" bulb was ·001, or about four times the absorption of the bulb employed in these experiments.

Measurement of the Current through the Gas.

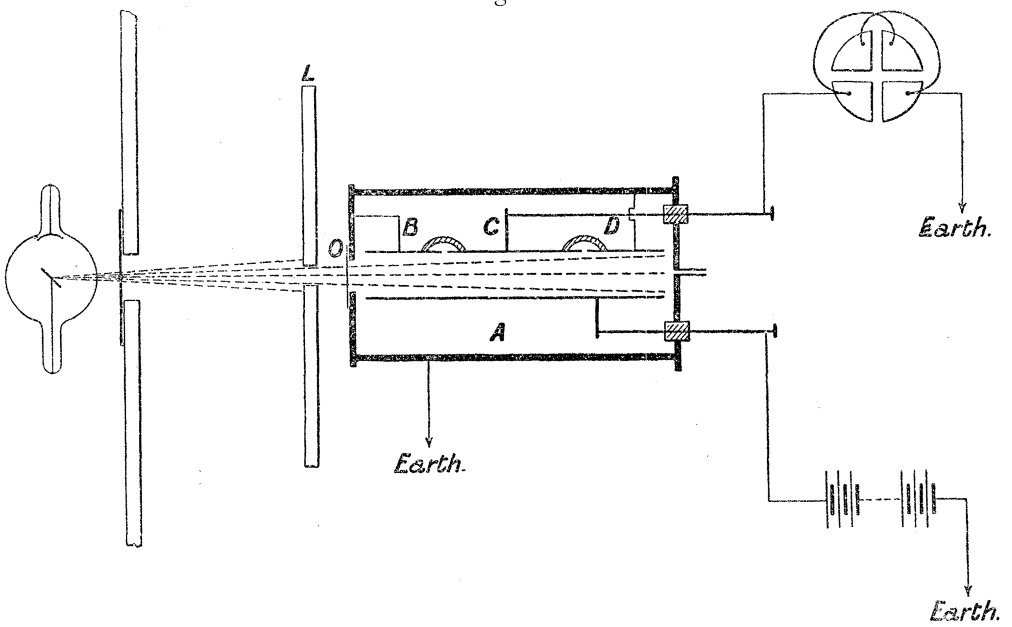
In order to determine the amount of ionization in a known volume of gas, the apparatus shown in fig. 6 was employed.

The rays passed into a brass cylinder, 12 centims. in diameter and 30 centims. in length, through a rectangular orifice, O, at one end covered with an aluminium window, 1 millim. in thickness. Inside the cylinder two parallel rectangular plates,

* E. Rutherford, 'Phil. Mag.,' January, 1899.

A and BCD, were fixed on a light wooden frame. The plate opposite to A was cut into three parts, B, C, D, and C was insulated from B and D. The plate A was connected to one pole of a battery of 310 volts, the other pole of which was connected to earth. The plate C was connected to one pair of quadrants of the electrometer, the other pair of which was connected to earth. The plates B and D were in connection with the cylinder, which was also connected to earth. The plates B and D thus corresponded to a partial guard ring for the plate C, and served two purposes. The electric field was rendered uniform from C to A, and most of the secondary radiation set up at the two ends of the cylinder was absorbed between A and B and between A and D, and thus did not produce appreciable ionization between A and C. A large lead plate, L, with a rectangular orifice, was so placed that the rays from the source passed into the cylinder, and did not fall on the parallel plates. This avoided the presence of secondary radiation. The two ends of the cylinders were covered inside with cardboard in order to make the amount of secondary radiation as small as possible. The amount of radiation set up at the surface of air and cardboard is very small. The amount of insulating material inside the cylinder was reduced as far as possible in order to avoid the collection of free charges on them, and consequent disturbance of the electric field. For this reason the plates were mounted on a wooden frame instead of an ebonite one. The wood was a sufficiently good conductor to quickly discharge any electrification that reached its surface.

Fig. 6.



The current between C and A is thus due only to the ions which were produced by the passage of the rays between them.

The length of the plate C was 12·06 centims., measuring from the centre of the air spaces. The distance between the plates was 4·16 centims. The rays, before entering

the cylinder, passed through a rectangular orifice in a thick lead plate. Knowing the distance from the source of the rays and the area of the opening, the area of a section of the cone of rays at any point in the cylinder could be determined.

The results calculated in this way were compared with the area of the impression on a photographic plate at different distances from the orifice, and it was found that the correction to apply for the source of the rays, not being a point source, was practically negligible.

Let I_2 be the intensity of the rays at the beginning of the plate C, and S the area of the cross-section of the cone of rays at that point. The energy crossing the surface per second is I_2S.

If there was no absorption of energy in the gas, the energy crossing the cross-section of the cone of rays at the further end of the plate C would be the same as at the beginning. But in consequence of absorption the energy crossing the surface per second is

$$I_2Se^{-\lambda l},$$

where l = length of the plate C, and λ = the coefficient of absorption of the rays in the gas. The energy absorbed in the gas per second is equal to

$$I_2S(1 - e^{-\lambda l}) = I_2S\lambda l$$

if λl is small, as was the case in the experiments.

The current between the plates A and C was determined for a voltage sufficient to move all the ions to the electrodes before any appreciable recombination could take place.

Let n = total number of ions produced per second.
i = current between the plates through the gas.
e = charge on an ion.
W = average energy required to produce an ion.

Then
$$Wn = I_2S\lambda l \quad \text{and} \quad i = n\epsilon;$$
$$\therefore \quad W = \frac{I_2S\lambda l\epsilon}{i}.$$

The value of I_2 was determined from the heating effect of the rays, as explained in the earlier part of the paper.

Let I_1 = intensity of the rays at the surface of the bolometer.
ρ_1 = transmission ratio of the rays when passing through the platinum grid.
Then
$$\text{energy absorbed in the grid per second} = I_1A(1 - \rho_1),$$
where A = area of grid.

Assuming the value of the intensity uniform over the surface of the grid, and equal to the value at the centre, the total energy absorbed in the grid is slightly less than

the above amount, and it has been shown earlier in the paper that very approximately the energy absorbed in the grid $= \cdot 98 I_1 A (1 - \rho_1)$.

In practice the current in the discharge cylinder was observed at the same time as the heating effect. The cylinder was placed behind the platinum grid in such a position that the rays entering the cylinder passed slightly to one side of the centre of the grid, thus avoiding the mica frame of the bolometer. The rays before entering the cylinder were cut down in intensity by their passage through the grid, by the enclosing envelope and the aluminium window in the discharge cylinder.

Let ρ_2 = transmission ratio of the rays through the platinum grid + the felt cover + the aluminium window, &c.

d_1 = distance of grid from source of rays.

Let d_2 = distance of the beginning of the plate C in the discharge cylinder from the source of the rays.

Then it can easily be seen that

$$\frac{I_2}{I_1} = \rho_2 \frac{d_1^2}{d_2^2} e^{-\lambda(d_1 - d_2)} \quad \ldots\ldots\ldots\ldots (1).$$

The factor $e^{-\lambda(d_1 - d_2)}$ is nearly equal to unity, and is the correction for the absorption of the rays in the gas between the grid and the discharge cylinder.

If H is the number of heat units communicated to the bolometer per second, then

$$\cdot 98 A I_1 (1 - \rho_1) = JH \quad \ldots\ldots\ldots\ldots (2),$$

and

$$W = \frac{I_2 S \lambda l \epsilon}{i} \quad \ldots\ldots\ldots\ldots (3).$$

Dividing (3) by (2) and substituting the value of I_2/I_1 from (1), we obtain

$$W = \frac{JH}{\cdot 98 A (1 - \rho)} \cdot \frac{S \lambda l \epsilon}{i} \cdot \rho_2 \cdot \frac{d_1^2}{d_2^2} e^{-\lambda(d_1 - d_2)}.$$

Determination of i.

The value of i was determined by an electrometer with an additional capacity of ·00248 of a microfarad in parallel. The heating effect on the bolometer and the quantity of electricity discharged between the plates of the cylinder were observed at the same time. A lead screen cut off the rays from the platinum grid and the discharge cylinder for 15 seconds after the bulb had started, for it was found that the rays gradually increased in intensity for the first 10 or 15 seconds. At the end of 15 seconds the lead screen was suddenly removed by a cord operated from a distance. After the passage of the rays for 30 or 45 seconds, the rays were stopped. The deflection from the zero of the bolometer was taken by one observer, while the

deflection of the electrometer was taken by another. In the later experiments the capacity of the electrometer and connections was $\frac{1}{27}$ of the capacity added, and the total capacity of the circuit was ·00257 of a microfarad.

The following is an example of the determination of i in electrostatic units :—

1 Clark cell of 1·434 volts E.M.F. gave 57·0 divisions on the electrometer scale. The deflection of the electrometer due to the passage of the rays for 30 seconds was 160 divisions.

$$i = \text{quantity of electricity per second}$$
$$= \frac{\cdot 00257}{10^6} \times \frac{160}{30} \times \frac{1\cdot 434}{57} \times 3 \times 10^9$$
$$= 1\cdot 03 \text{ electrostatic units.}$$

Determination of the Absorption of the Rays in the Bolometer, the Aluminium Window, &c.

The values of ρ_1 and ρ_2 were determined electrically by utilising the discharge cylinder of fig. 6. The rate of discharge in the cylinder was observed with the grid before the hole in the lead plate and then without the grid. The ratio of the currents in the two cases is proportional to the ratio of the intensities, since the ionization is proportional to the intensity of radiation. A mean value of the ratio for different portions of the grid was taken, and it was found that $\rho_1 = \cdot 453$. It is thus seen that the intensity of the radiation was cut down to a little more than half in passing through the platinum grid. The value of ρ_2 was determined in a similar manner. The intensity of the rays in this case was cut down more in consequence of passing through a thickness of felt, an aluminium window of ·1 centim. thickness, and a thin layer of aluminium, as well as the platinum grid. The value found for this ratio was $\rho_2 = \cdot 31$.

The absorption of the rays in the mica frame appears in the values of ρ_1 and ρ_2. The absorption, however, was small and practically negligible in any case.

Dimensions of the Apparatus and Values of Constants.

The area of the rectangular hole through which the rays passed into the discharge cylinder, and from which S was calculated, was 7·1 sq. centims. The length of the centre plate in the discharge cylinder was 12·06 centims. For most of the experiments, the distance d of the grid from the source of rays was 26·0 centims., and the distance of the hole in the lead plate from the source was 45·2 centims.

Area of platinum grid was 92·6 sq. centims.
Mean value of $\lambda = \cdot 000279$.
Value of $\epsilon = 6\cdot 5 \times 10^{-10}$ electrostatic unit.

The correction for the absorption in air between the grid and the discharge cylinder was negligible.

The following table gives the values of i, H, and W for different times of the exposure to the rays:—

Time of exposure to rays.	i in electrostatic units.	H in calories.	W in ergs.
45 secs.	·894	$1{\cdot}49 \times 10^{-4}$	$2{\cdot}22 \times 10^{-10}$
,,	·976	$1{\cdot}56 \times 10^{-4}$	$2{\cdot}13 \times 10^{-10}$
,,	1·045	$1{\cdot}47 \times 10^{-4}$	$1{\cdot}87 \times 10^{-10}$
,,	1·115	$1{\cdot}57 \times 10^{-4}$	$1{\cdot}82 \times 10^{-10}$
,,	·996	$1{\cdot}38 \times 10^{-4}$	$1{\cdot}84 \times 10^{-10}$
30 secs.	1·00	$1{\cdot}34 \times 10^{-4}$	$1{\cdot}79 \times 10^{-10}$
,,	1·07	$1{\cdot}47 \times 10^{-4}$	$1{\cdot}83 \times 10^{-10}$
,,	1·03	$1{\cdot}45 \times 10^{-4}$	$1{\cdot}87 \times 10^{-10}$
,,	1·09	$1{\cdot}41 \times 10^{-4}$	$1{\cdot}72 \times 10^{-10}$

The mean value of W, the energy required to produce an ion in air at atmospheric pressure and temperature, is given by

$$W = 1{\cdot}90 \times 10^{-10} \text{ erg.}$$

The energy required to produce a positive and a negative ion from a neutral molecule is twice this amount, and since one ion cannot be produced without the other, then $3{\cdot}8 \times 10^{-10}$ erg is the smallest amount of energy that will produce ions in air.

The mean intensity of the rays in absolute measure at the surface of the bolometer is given by

$$JH = {\cdot}98AI_1(1 - \rho_1).$$

Taking the value of H as $1{\cdot}5 \times 10^{-4}$ calorie, we find that

$$I_1 = 127 \text{ ergs.}$$

On account of the very short duration of the rays from each discharge, the maximum intensity of the radiation at any time is probably over a thousand times greater than the above value.

The energy absorbed per second in producing ions in the cylinder $= \frac{i}{\epsilon} W = {\cdot}29$ erg, taking $i = 1$ E.S. unit.

This absorption of energy is spread throughout a volume of over 100 cub. centims. of the gas, so that the absorption of energy per cub. centim. in the air is very small.

The value of W, the ionic energy, is seen to depend on the measurement of the current through the gas, the coefficient of absorption, and the heating effect of the rays. The absorption of the rays in the gas has to be determined separately from the current and heating effect, and an uncertainty consequently arises on account of

the variation of the penetrating power of the rays as the bulb varies. The value of λ determined for the rays, under different conditions as regards the frequency of the Wehnelt interrupter, was found to be approximately the same, after the bulb had been in constant use for several months. It is probable that the type of rays does not on an average vary much from day to day, but the greatest source of error is probably due to the assumption that the rays are homogeneous in character. RÖNTGEN and others have shown, from experiments on the absorption of successive thicknesses of metal, that rays are not simple in character, but contain rays of widely different order of penetrating power, so that the value of λ is the mean value for the different types of rays.

The value of W also depends upon the value of ϵ, the charge on an ion, and if future investigations should assign a different value to ϵ, the value of W would be altered in a like ratio.

Energy required to produce an Ion in other Gases.

When the energy required to produce an ion in one gas is known, the energy required to produce an ion in another gas can be determined from the ratio of the absorptions of the rays and the intensity of ionization in the gases.

Let n_1 and n_2 be the number of ions produced per cub. centim. in two gases.

Let λ_1 and λ_2 be the coefficients of absorption.

Let W_1 and W_2 be the energies required to produce ions in the two gases.

Let i_1 and i_2 be the maximum currents through the gases.

Then for the same intensity of rays,

$$\frac{\text{absorption of energy in gas}_2}{\text{absorption of energy in gas}_1} = \frac{\lambda_2 I}{\lambda_1 I} = \frac{n_2 W_2}{n_1 W_1}$$

$$= \frac{i_2 W_2}{i_1 W_1}, \text{ since } i_1 = n_1\epsilon \text{ and } i_2 = n_2\epsilon, \text{ assuming charges on the ions are equal.}$$

Therefore

$$\frac{W_2}{W_1} = \frac{\lambda_2}{\lambda_1} \cdot \frac{i_1}{i_2}.$$

The ratios λ_2/λ_1 and i_1/i_2 can be readily determined, and if W_1 is known, then W_2 can be calculated without recourse to experiments on the heating effect of the rays in each case.

The value of λ_2/λ_1, the ratio of the absorption coefficient of carbonic acid gas to that of air, was found to be 1·59 for the rays employed. The ratio i_2/i_1 of the current in air and carbonic acid gas for a potential difference of 300 volts was found to be 1·43.

Therefore the energy required to produce an ion in carbon dioxide

$$= \frac{1{\cdot}59}{1{\cdot}43} W_1 = 1{\cdot}11 W_1 = 2{\cdot}11 \times 10^{-10} \text{ erg.}$$

This value is a little higher than in the case of air. The measured amount of i_2, the current in carbon dioxide, was somewhat less than the maximum, since the electromotive force applied was not sufficient to move all the ions to the plates before recombination. A correction for this would make the values for air and carbon dioxide more nearly equal.

Taking the value 1·53, found by J. J. Thomson,* for the relative ionization in carbonic acid and air, the ionic energies are nearly the same.

The results for air and carbon dioxide show that the energy required to produce ions in the two gases is not very different. The results of a previous paper† showed that the absorption of X rays in gases was roughly proportional to the ionization produced. From this it follows that the energy required to produce ions in the gases examined was, roughly, the same.

The results obtained with uranium radiation‡ showed that the total number of ions produced by complete absorption of the radiation in air, oxygen, hydrogen, carbonic acid gas, hydrochloric acid gas, and ammonia were approximately the same. The results in that case were more readily obtained as the radiation was almost completely absorbed in a few centims. of the gas, and the maximum current through the gas was a measure of the total number of ions produced.

The recent results of McLennan§ also point strongly in the same direction. In his experiments, cathode rays were passed out of the discharge tube into another vessel, and the maximum current produced by the cathode rays was found for different gases. Using a constant supply of cathode rays, the current, *i.e.*, the total number of ions produced, was independent of the nature of the gas (provided the pressure of the gas was adjusted to give the same absorption of the rays in each case). The gases examined were air, hydrogen, oxygen, nitrogen, carbonic acid, nitrous oxide, and the total number of ions produced in them was nearly the same. Assuming that the same proportion of energy of the cathode rays was used up in producing ions in the gases, it follows that the energy required to produce an ion in all the gases is the same.

The results on the ionization of different gases by the agency of Röntgen, Becquerel, and cathode rays all strongly point to the conclusion that the same energy is required to produce an ion whatever the gas.

Variation of Ionic Energy with Pressure.

It has been shown earlier in the paper that from half an atmosphere to three atmospheres' pressure the absorption is proportional to the pressure. A special

* J. J. Thomson, 'Camb. Phil. Soc. Proc.,' vol. 10, Part I.

† E. Rutherford, 'Phil. Mag.,' April, 1897.

‡ E. Rutherford, 'Phil. Mag.,' January, 1899.

§ 'Roy. Soc. Proc.,' 1900; 'Phil. Trans.,' A, vol, 195.

investigation has shown that for the same range the intensity of the ionization is also approximately proportional to the pressure. This shows that for the pressures examined the ionic energy is independent of the pressure. The results on the variation of absorption with pressure for uranium* and thorium† radiation also point to the same conclusion.

In order to fully establish such a general law that the energy to produce an ion is independent of the gas and its pressure, a large number of careful experiments will be required. The results so far obtained can only be considered to show that such a law is approximately true. It is intended to continue these investigations on ionic energy for other gases besides air and carbonic acid.

Deductions from the Results.

If ions of the same kind are produced in a gas by different agencies, it is probable that the same amount of energy has been absorbed to produce the ions in the different cases. The only test we have at present for equality is to compare the velocity of the ions in the gas for a potential gradient of 1 volt per centim. J. J. Thomson has shown that the charge on an ion produced by Röntgen rays is probably the same for the gases hydrogen, air, oxygen, and carbonic acid, and Townsend‡ that it is equal to the charge on a hydrogen ion in the electrolysis of water. The velocity of the ions in a given electric field depends upon the ratio ϵ/m of the charge to the mass of the ion, and thus if the velocities of ions produced in the same gas by different agencies are the same, the masses must be the same, since the charges are equal.

It has recently§ been shown that the ions in the "electric wind" travel in air with the same velocity as the ions produced by rays. The energy used up in producing the ions can thus be immediately calculated.

Let i = the current through the gas due to the electric discharge from a wire or point.

Energy absorbed in producing ions $= n\,\mathrm{W} = \frac{i}{\epsilon}\,\mathrm{W}$,

where n is the number of ions produced per second and ϵ the charge.

Therefore, neglecting recombination of the ions,

$$\frac{\text{Energy required to produce ions}}{\text{Total loss of energy}} = \frac{\frac{i}{\epsilon}\,\mathrm{W}}{\mathrm{V}i} = \frac{\mathrm{W}}{\epsilon}\,\frac{1}{\mathrm{V}},$$

where V is the potential of the discharging wire.

* E. Rutherford, 'Phil. Mag.,' January, 1899.
† R. B. Owens, 'Phil. Mag.,' October, 1899.
‡ 'Phil. Trans.,' A, 1899.
§ Chattock, 'Phil. Mag.,' October, 1899.

If V = 6000 volts = 20 electrostatic units, then the proportion of the total loss of energy used up in the production of ions

$$= \frac{1{\cdot}90 \times 10^{-10}}{6{\cdot}5 \times 10^{-10}} \cdot \frac{1}{20} = \frac{1}{69} \text{ approx.}$$

Thus quite an appreciable proportion of the total energy supplied is absorbed in producing ions. The proportion decreases with the increase of voltage.

Distance between the Ions in a Molecule.

If we suppose that most of the energy required to produce a positive and a negative ion from a neutral molecule is due to the work done in separating the ions from each other against the forces of electrical attraction, we can at once form an approximate estimate of the distance apart of the charges in the molecule.

The work done in separating a charge $+\epsilon$ from a charge $-\epsilon$, both charges supposed concentrated at points from a distance r to an infinite distance, is equal to ϵ^2/r.

If this is equal to the energy required to produce two ions, then

$$\frac{\epsilon^2}{r} = 3{\cdot}8 \times 10^{-10},$$

since

$$\epsilon = 6{\cdot}5 \times 10^{-10}$$

$$r = 1{\cdot}1 \times 10^{-9} \text{ centim. approximately.}$$

The average diameter of an atom, calculated from various methods, is about 3×10^{-8} centim. This is a very much greater distance than the value found for the distance apart of the charges on the ions in a molecule. The results support the theory advanced by J. J. Thomson, that ionization is produced by the removal of a negative ion from the molecule, and that the negative ion is only a small portion of the mass of the atom. The positive ion is supposed to remain attached to the rest of the molecule. It is to be expected from the theory that the distance of the charges from each other would be less than the diameter of an atom.

The energy required to produce an ion in air is very much greater than the energy required to produce an ion in the electrolysis of water. If V (1·46 volts) is the least E.M.F. required to dissociate water, the work done in moving a quantity of electricity ϵ is $V\epsilon$. The work done in producing an ion thus is $V\epsilon$ or $\frac{1{\cdot}46}{300} \times 6{\cdot}5 \times 10^{-10} = 3{\cdot}16 \times 10^{-12}$ erg, or about $\frac{1}{60}$ of the energy required to produce an ion in air by the agency of X rays, so that in water the ions are about two atoms apart

Least Potential required to produce a Spark in Air.

The ions in the "electric wind" in air have been shown to move with the same velocity as the ions produced by X rays. It is probable that the passage of a spark between two electrodes is heralded by the production of ions in the gas, and that these ions are of the same kind as the ions in air produced by X rays.

Let V be the difference of potential between two electrodes in air, one electrode being connected to earth. Suppose a pair of ions to be produced and to travel to the electrodes. A quantity of energy $3{\cdot}8 \times 10^{-10}$ erg is absorbed in their production, while the energy of the electric system is diminished by an amount $V\epsilon$. The energy required to produce the ions must be derived from the electric energy of the system. In order for an ion to be produced consistent with the conservation of energy, we must have V of such value that $V\epsilon$ is greater than the energy required to produce a pair of ions.

$$\therefore \quad V > \frac{3{\cdot}8 \times 10^{-10}}{6{\cdot}5 \times 10^{-10}} \text{ electrostatic unit.}$$

$$\therefore \quad V > 175 \text{ volts.}$$

Now Peace (J. J. Thomson, 'Recent Researches,' p. 89) has shown that it is impossible to produce a spark in air below about 300 volts, however close the electrodes are together. This is a somewhat greater value than the one found above, but is of the same order. Strutt* has recently shown that the minimum potential difference for the passage of a spark in pure nitrogen is about 251 volts. As most of the ions in air are probably produced from the nitrogen molecules, this value makes the agreement still closer. The results obtained would indicate that it would be impossible to produce an ion, and therefore an electric spark, below 175 volts. If the energy required to produce an ion were the same at all pressures, the minimum sparking potential according to the above theory would be unaltered. This is borne out by Peace's results (*loc. cit.*, p. 86), where it is shown that the minimum potential difference for a spark between spherical electrodes ·001 centim. apart is approximately the same for pressures from 300 to 50 millims. of mercury. The minimum potential rises below 50 millims., indicating that the energy required to produce an ion may possibly increase below that pressure.

This theory would suggest that the minimum potential required to produce a spark conversely might be used as a means of determining the energy to produce an ion. The phenomenon, however, is more complex than this would indicate. The minimum sparking potential is to a small extent influenced by the metal used for the electrodes and also by the gas, and moreover it would leave unexplained the remarkable fact that when the electrodes are a small distance apart the spark does not follow the shortest path (*loc. cit.*) between them.

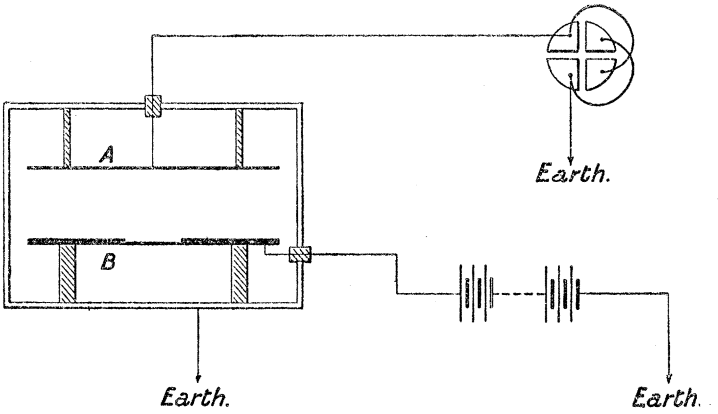
* 'Phil. Trans.,' A, 1900.

Energy of Radiation of Radio-active Substances.

In a previous paper it has been shown that the ions produced in air by uranium radiation have the same velocity as the ions produced by Röntgen rays. On the assumption that the same amount of energy is required to produce the ions, whether the agency is Röntgen or uranium rays, the energy of the radiation given out into the gas can be at once determined. Fig. 7 shows the arrangement of the apparatus to determine the current through air produced by the uranium rays.

Two large parallel plates, A and B, 4·1 centims. apart, were insulated from each other. A was connected to the electrometer in the usual manner, and B was connected to one pole of a battery of small cells of 310 volts. The uranium oxide employed was placed in a square shallow hole cut in a lead plate placed on the plate B. The current between A and B was determined for a potential difference of 310 volts, an amount sufficient to practically remove all the ions before recombination.

Fig. 7.



Since the area of the uranium surface is small compared with the area of the plates between which the uranium was placed, the total energy per second emitted by the surface S of uranium is approximately equal to IS, where I is the intensity of the radiation at the surface of the uranium.

If λ is the coefficient of absorption of the rays in air, and W is the energy required to produce an ion, the energy absorbed per second between the plates at a distance d apart is equal to

$$\mathrm{IS}\{1 - e^{-\lambda d}\} = n\mathrm{W} = \frac{i}{\epsilon}\mathrm{W},$$

where n is the number of ions produced per second, i is the current, and ϵ the charge on an ion.

The total energy emitted per second is equal to

$$\frac{i\mathrm{W}}{\epsilon(1 - e^{-\lambda d})}.$$

In the case of uranium it has been shown (*loc. cit.*) that apparently two types of radiation are emitted, one of which is readily absorbed in air. The ionization due to the more penetrating rays is in general a small part of the total, especially for thin layers of uranium; so that in the present calculation we will only consider the energy given out by uranium in the production of the more absorbed type of radiation.

The intensity of the radiation emitted from uranium falls to half its value after passing through 4·3 millims. (*loc. cit.*, p. 128). Therefore $\lambda = 1{\cdot}6$.

Since $d = 4{\cdot}1$, therefore $e^{-\lambda d}$ is small and may be neglected.

Thus the energy given out into the air is $\frac{i}{\epsilon}$ W. Now for a thick layer of uranium oxide (3·6 grammes spread over a surface of 38 sq. centims.) the current $i = {\cdot}0515$ electrostatic unit. Thus the energy emitted per unit area of uranium surface per second

$$= \frac{{\cdot}0515}{6{\cdot}5 \times 10^{-10} \times 38} \times 1{\cdot}90 \times 10^{-10} = {\cdot}0004 \text{ erg}$$

$$= 10^{-11} \text{ calorie per second, approximately.}$$

This amount of energy would suffice to raise 1 cub. centim. of water 1° C., assuming no radiation of heat, *in about* 3000 *years*.

It is a difficult matter to determine the total energy given off in the radiation by a given weight of uranium on account of the ease with which the radiation is probably absorbed by the heavy metal uranium itself in its passage through it. Some experiments were made on the current due to a given surface of uranium oxide when different depths of the active material were spread over it. The following are some of the results :—

Surface of Uranium Oxide = 38 sq. centims.

Weight of uranium oxide in grammes.	Current in E.S. units per second.
·138	·0201
·365	·0365
·718	·0471
1·33	·0515
3·63	·0560

The uranium oxide in the form of a fine powder was dusted on uniformly by means of a fine wire gauze. The results show that the current per gramme of uranium oxide is greater for small than for large thicknesses. Even with a very thin layer of uranium oxide in the form of powder it is probable that a large proportion of the

energy emitted (supposed produced throughout the volume of the substance) is absorbed in the substance itself. An approximate determination of the total energy per second that can be radiated by 1 gramme of uranium could be determined by dissolving a few crystals, say, of uranium nitrate in water and pouring the solution over a large surface area. On evaporating the water a very thin film of the nitrate would be left on its surface. In such a case the rays produced throughout the volume of the film should reach the surface without much loss due to absorption, and the maximum current through the gas would be proportional to the total energy radiated. In this case half of the total energy would be absorbed in the substance on which the film was placed and only half would be efficient in producing ions.

In order to obtain an approximate value of the total energy of radiation, uranium oxide in the form of a very fine dust was spread over a surface of 38 sq. centims.

Weight of uranium oxide = ·138 gramme.

Current = ·02 electrostatic unit.

Total energy radiated into the gas per second = $1{\cdot}4 \times 10^{-10}$ calorie.

Energy per gramme of uranium oxide radiated into the air

$$= 10^{-9} \text{ calorie per second.}$$

$$= {\cdot}032 \text{ calorie per year.}$$

In our present state of knowledge it is uncertain whether the radiating power is confined to the surface of the uranium or is given out uniformly throughout the mass. In any case, the total energy radiated is probably greater than the value above on account of absorption of the radiation in the uranium itself, and also on account of the existence of a more penetrating type of radiation, the energy of which has been neglected in the above calculations.

Energy of Thorium Radiation.

The apparatus employed was the same as that for uranium. Thorium oxide was employed and the following results were obtained. Area of surface = 38 sq. centims. :—

Weight of thorium oxide.	Current.
gramme.	
·339	·0445 electrostatic unit per second.
·665	·0622 „ „ „

In previous papers by OWENS* and RUTHERFORD,† the behaviour of thorium oxide as a radio-active substance has been carefully examined. It has been shown that thorium compounds give out a material emission of some kind, which possesses temporary radio-active properties. This emanation is most apparent with thick layers of thorium oxide. In the present case the layer was not thick enough to give out much emanation, and the rate of discharge was due to the radiation alone. OWENS has shown that the radiation from thorium is approximately homogeneous.

The value of λ, the coefficient of absorption of thorium radiation in air, is ·69 and $d = 4{\cdot}1 \therefore 1 - e^{-\lambda d} = {\cdot}96$.

Thus for a weight of ·665 gramme the total energy radiated into the gas per unit area $= \frac{iW}{{\cdot}96\epsilon A}$ erg, and, on the same assumptions as for uranium, the energy radiated into the air per second $= 1{\cdot}2 \times 10^{-11}$ calorie, a somewhat greater value than for an equal weight of uranium oxide.

Excited Radio-activity due to Thorium.

Thorium compounds, in addition to the property of giving out a radio-active emanation, possess the power of exciting temporary radio-activity on all substances in their neighbourhood. The excited radiation is homogeneous in character, and is of a more penetrating type than the radiation from either uranium or thorium. The intensity of the excited radio-activity can be greatly increased by concentration on the negative electrode of small area by means of a strong electric field. On the assumption that the energy of the radiation excited on the electrode is dissipated in producing ions, an estimate can be formed of the energy stored up on the electrode.

In a particular experiment a fine platinum wire, ·018 centim. in diameter and 1 centim. long, caused the separation of about 10 coulombs of electricity before the radio-active power was lost. This corresponds to an emission of 2×10^{-5} calorie.

This by no means inconsiderable quantity of energy is in some way derived from the surface of a platinum wire ·056 sq. centim. in area, without the slightest appreciable change either in the weight or appearance of the wire.

Radium and Polonium.

The question of the equality of the velocity of the ions, produced by thorium radiation and the rays from the powerful radio-active substances radium and polonium, with the velocity of the ions produced by X rays, has not been specially investigated, but from the very close similarity of the types of these radiations, it seems very probable that the ions produced by all are the same.

* 'Phil. Mag.,' October, 1899.

† 'Phil. Mag.,' January and February, 1900.

In one respect, however, some of the radio-active substances, notably radium, differ in their type of radiation from X rays. BECQUEREL, CURIE, and others, in a series of papers in the 'Comptes Rendus,' have shown that radium gives out a type of rays which are easily deflected by a magnet. This emission of rays similar in character to cathode rays of low velocity is very remarkable, but does not seem to be a necessary accompaniment of a radio-active substance. For example, GIESEL found polonium gave out rays deflected by a magnet, while BECQUEREL could obtain no magnetic action for the same substance. The rays which are deflected by a magnet seem to be present or absent according to the mode of preparation of the substance, and depend possibly on the age of the specimens. Two impure and not very sensitive specimens of radium and polonium obtained from pitchblende have been tested by one of us, but no magnetic action has been observed. BECQUEREL has found no trace of magnetic action in uranium radiation, and one of the authors has tested both uranium and thorium radiations in a magnetic field at atmospheric pressure and obtained negative results.

The experiments of CURIE and BECQUEREL have shown that, in radium, two types of rays are present, one of which is deflected by a magnetic field and the other is not. The non-deflected type is similar in character to secondary X rays, and the deflected ones similar to low velocity cathode rays.

We thus see that the phenomena exhibited by the radio-active substances are not simple, and that they differ from one to the other. It is still possible, however, to form an approximate estimate of the energy of the radiation whatever its kind, provided the energy is all completely absorbed in ionizing the gas, and produces ions of the same kind. It seems probable that the radium rays acted on by a magnetic field are a type of cathode rays, and that they ionize the gas in their passage through it. The results of MCLENNAN* clearly show that the energy of the cathode rays is lost in its passage through the gas, due partly to the work done in ionizing the gas in its path. Provided the ions produced by the deflected and undeflected rays of the radio-active substances are the same, and absorb the same amount of energy in their production, the relative energies of the radiations emitted can be compared by noting the total maximum current produced by the rays when completely absorbed between the electrodes.

If n = the ratio of the currents between parallel plates for equal areas and thicknesses of the test substances and uranium oxide when the plates are at a sufficient distance apart to approximately absorb all the rays, then

> Energy radiated out by the test substances into the gas = $n \times$ the energy radiated by an equal area of uranium oxide.

This will probably apply roughly to the conductivity produced by the deflected and undeflected rays.

* 'Roy. Soc. Proc.,' vol. 66, 1900; 'Phil. Trans.,' A, vol. 195.

In some experiments CURIE mentions using a specimen of radium 100,000 times more active than uranium. If this applies to measurement for equal weights and areas of radium and uranium, then the total energy radiated out into the gas by 1 gramme weight of radium is not less than 10^{-4} calorie per second, or 3200 calories per year.

It is evident that, unless energy is supplied from external sources, the substance cannot continue emitting energy at such a rate for many years, even supposing a considerable amount of energy may possibly be derived from rearrangements of the components of the molecule.

In the light of the results on the amount of energy given out by radio-active substances, it is of interest to consider some speculations as to the origin of the rays, and of the supply of energy required for a continuous emission of the radiation.

We will first briefly review the state of our present knowledge of the radio-active substances. Uranium, the first of the radio-active substances discovered, has been closely investigated. BECQUEREL has shown that it gives out radiation constantly from year to year, even when placed in the dark. The radio-activity is preserved in solution, and persists if the substance is recrystallised in the dark. The radiation given out is independent of the gas around it, and of the pressure of the gas, and is not much affected by considerable changes of temperature. The same radiation is given out by all the uranium compounds. The radio-activity appears to depend on the uranium molecule alone, and not what it is combined with. Pitchblende and other uranium minerals are active, and, as far as experiments have gone, continue radiating indefinitely.

In considering the question of the emission of energy per unit weight of uranium, an important point arises which it is difficult to decide satisfactorily by experiment, viz., whether the radio-activity is confined to the surface or possessed by the whole mass of the substance. At first sight the radio-activity appears to be superficial, since the intensity of the radiation does not increase with increase of thickness of uranium. Such an action, however, is to be expected, even though there is volume radio-activity, since the radiation can only penetrate to the surface from a very short depth below the surface. The increase of the intensity of the radiation with increase of thickness for thin layers and the action of solutions support, as far as they go, the supposition that the activity is throughout the volume. The energy given out in the interior of the substance would most probably be dissipated as heat in the material. If the radio-active power is possessed by the whole volume, it follows from the above supposition that the mineral pitchblende must have been radiating energy since its formation as a mineral. If we suppose the radiation has been going on constantly at its present rate in the course of 10,000,000 years, each gramme of uranium has radiated at least 300,000 calories.

It is difficult to suppose that such a quantity of energy can be derived from regrouping of the atoms or molecular recombinations on the ordinary chemical theory.

This difficulty is still further increased when we consider the emission of energy from radium, a substance 100,000 times more active than uranium. The emission of energy in that case is, at least, 3000 calories per year. If future experiments should show that radium, as well as uranium, gives out radiation at a constant rate from year to year, in order to account for such a rapid emission of energy, it would be necessary to suppose that the radio-active substance in some way acts as a transformer of energy. Such a supposition does not seem probable, and leads us into many difficulties.

On the view, however, advanced recently by J. J. Thomson, that an atom is not simple, but composed of a large number of positively and negatively charged electrons, the possible energy to be derived from the closer aggregation or regrouping of the components of a molecule is very much greater than on the atomic theory, as ordinarily understood. The energy required to completely dissociate a molecule into its component electrons would be many thousand times greater than the energy required to dissociate a molecule into its atoms. The energy that might be derived from a greater concentration or closeness of aggregation of the components of such a complex molecule would possibly be sufficient in the case of uranium to supply the energy for the emission of radiation for long periods of time. The sudden movements of electrons would set their charges in oscillation, and give rise to a series of electromagnetic pulses corresponding to X rays. The remarkable property of some of the radio-active substances in naturally emitting a kind of cathode rays shows that the present views of molecular actions require alteration or extension in order to explain such phenomena. The energy that might possibly be derived from regrouping of the constituents of the atom would not, however, suffice to keep up a constant emission of energy from a strong radio-active substance, like radium, for many years. It is of importance that experiments to test the constancy of the radiations of a powerful radio-active substance, like radium, should be carried out at definite intervals. If the radiation should keep constant from year to year, it would be strong evidence that the energy of the radiation was not derived at the expense of the chemical energy of the radio-active substance.

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