of a calcium atom are approximately 400 and 1000 volts respectively (computed from values given by Hartree for atoms of neighbouring elements), and the values of j or $\sqrt{j}$ are given in columns (3) and (4) of the table. In order to obtain the contribution to F_u the amplitude of the unmodified wave leaving the electron must be multiplied by the diffraction factor, $C(\beta)$. According to Stoner there are six electrons describing 2_2 orbits in the calcium atom, and the contribution δF_u to F_u from this class of electrons is therefore $6jC(\beta)$ or $6\sqrt{j}C(\beta)$, according to the supposition made as regards the nature of the scattering. The values of δF_u are given in the fifth and sixth columns. The contributions to F on the classical theory are given in the last column for comparison.

In the case of elliptic orbits different elements of the orbit defined by the distance of the electron from the nucleus have been considered separately, the calculation for each element being similar to that for a circular orbit. The value of F_u for the whole ion is obtained by adding up the contributions, δF_u, from the various classes of electrons in the ion.

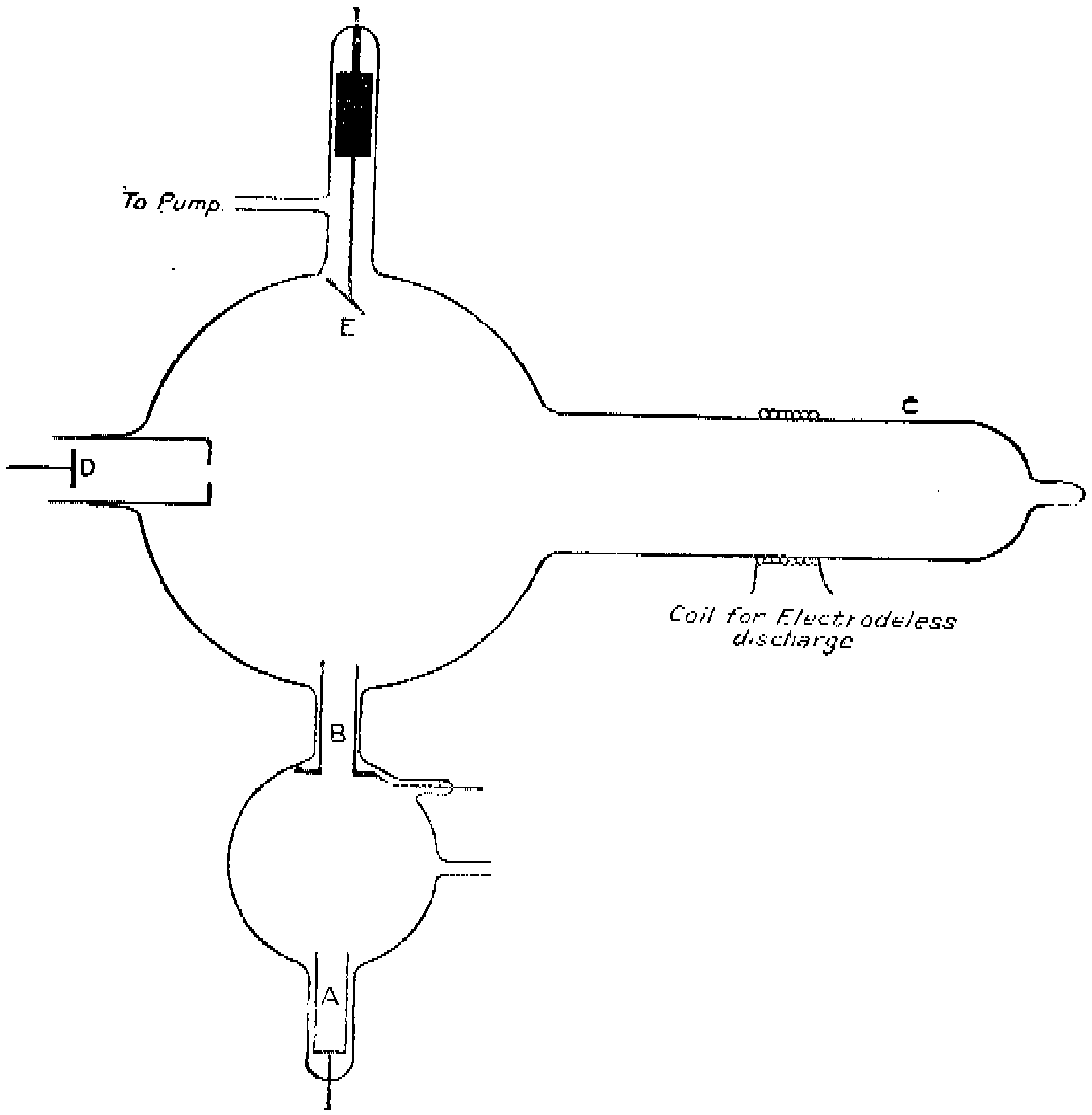
LIX. *Radiation produced by the Passage of Electricity through Gases.* *By* Sir J. J. Thomson, *O.M., F.R.S.*[*]

In the Philosophical Magazine for May 1925 I gave an account of experiments which showed that the passage of the electric discharge through gases at low pressures gives rise to the emission of radiations which, like radiation in the extreme ultra-violet or very soft X-rays, are absorbed with such rapidity that they cannot penetrate more than a thin layer of gas unless the pressure is very low; as they give rise to very intense ionization, they are of fundamental importance in the theory of the electric discharge through gases. In this paper I describe a series of experiments on the sources and characteristic properties of these radiations.

The experiments described in the earlier paper were made on the radiation coming from the space between the anode and cathode of a discharge-tube; in this region there are both moving electrons and moving positive ions, and their radiations are superposed. In the following experiments the effects due to the electrons and the positive ions were studied separately. For this purpose streams of either cathode or positive rays were isolated and sent past the window through which the radiations passed to the apparatus by which they were detected and tested.

The electrodes A and B (fig. 1) for the discharge were placed at one end of a long tube. B is a brass or aluminium cylinder fitting tightly into the glass tube; a hole is bored out along the axis of this cylinder. A was in some cases a plane disk with its plane at right angles to the axis of B;

Fig. 1



in other cases it was a tube whose axis was in the same straight line as the axis of B. When A is made cathode a beam of cathode rays, and when it is made anode a beam of positive rays, streams through the boring in the cylinder B and excites radiation in the gas. This radiation is detected by the photoelectric effect it produces when it falls upon a polished metal disk D which is connected with a Dolezalek electrometer. In order to screen off from the disk the effects which would be produced by ions diffusing from the discharge-tube two methods have been employed, which

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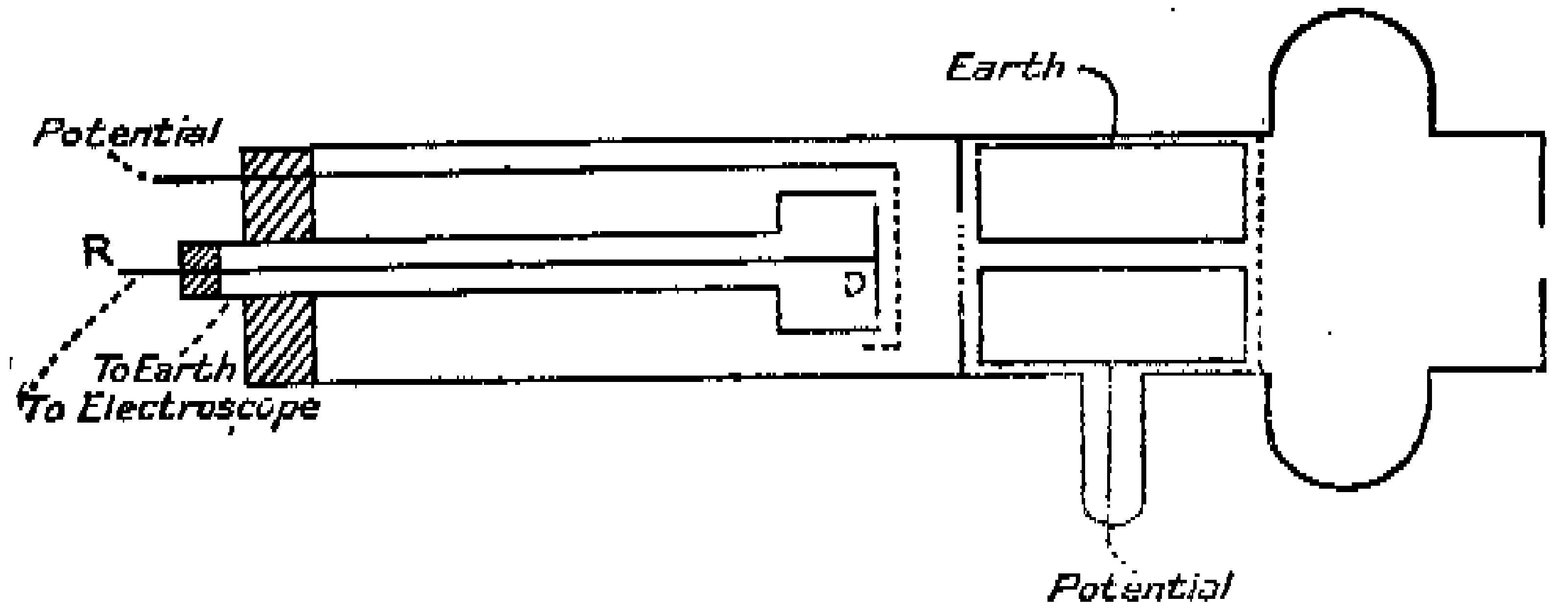
[*] Communicated by the Author.

are described on pp. 769 and 762, Phil. Mag. xlix. (1925). In the first of these methods the ions are stopped by a strong electric field and the radiation has not to pass through any solid obstacle, but passes through a slit between two half-cylinders insulated from each other and connected with the terminals of a battery of storage cells ; there is thus a strong electric field across the slit. The geometry of the apparatus was such that the beam of rays was parallel to the slit and was in full view of the disk D. The details of the electrical connexions and the position of screens of wire gauze to screen off any electrostatic effects due to the charges on the half-cylinders are indicated in fig. 2.

The efficiency of the screen for stopping the ions and electrons coming from the discharge was tested by increasing the potential difference between the half-cylinders. With the potentials used this increase produced no change in the deflexion of the electrometer, nor was any difference produced by reversing the direction of the field between the slits.

Fig. 2.



The other method used to screen off the ions is to place the disk D in a brass tube with a very thin celluloid window at one end ; the celluloid stops the ions, but allows some of the radiation to get through. I showed in the previous paper that even the thinnest celluloid obtainable stops all but a small fraction of the soft radiation coming from the tube.

Special precautions were taken to isolate the radiation coming from the molecules of the gas from that due to the impact of the electrons or positive rays against the walls of the discharge-tube. A side tube C (fig. 1) about 20 cm. long and 5 in diameter was used on to the main tube opposite to the testing apparatus, and the slit between the cylinders used to produce the screening electric field stopped down until the only part of the glass of the tube visible from the photoelectric disk was that at the far end of the tube C, which is far out of the path of the electrons.

The intensity of the stream of cathode or positive rays is estimated by the charge they give to the disk E (fig. 1), which is connected to earth through a high-resistance galvanometer. The disk can be moved backwards and forwards down the tube and can be brought within view of the disk connected with the electrometer ; when in this position the radiation due to the impact of the rays against the disk E, as well as that coming from the molecules of the gas, falls upon the testing apparatus, and by comparing the effects when E is in this position with those when it is pushed back we can estimate the relative intensities of these radiations.

Radiation due to the passage of cathode rays through the gas.

When the electrode A (fig. 1) was the cathode and a stream of cathode rays went through the opening in B past the window leading to the testing apparatus, the electrometer received a continuously increasing positive charge ; this we ascribe to the ejection of electrons from the disk connected with the electrometer, due to the incidence of the radiation excited by the cathode rays in their course through the gas. If the stream of cathode rays is deflected by a magnet so that it can no longer be seen from the disk connected with the electrometer, the deflexion of the electrometer ceases, showing that the radiation came from the gas traversed by the beam of cathode rays and not from the walls of the tube.

If the target E is moved down the tube until it comes within sight of the disk connected with the electrometer so that the radiation excited by the incidence of the cathode rays on the metal target falls upon the disk, the deflexion of the electrometer is increased greatly, sometimes more than a hundredfold.

Radiation excited by positive rays.

When A (fig. 1) is made anode a beam of positive rays passes through the gas in sight of the disk connected with the electrometer, the electrometer acquires a continuously increasing charge of positive electricity, showing that the passage of positive rays through the gas excites radiation. In fact, when the electric discharge is produced by an induction coil the deflexion of the electrometer is greater when the induction coil is arranged to send a beam of positive rays through the tube than when the coil is reversed, so that cathode rays pass in front of the window. The number of positive and cathode rays passing past the window in unit time can be ascertained from the deflexions of the galvanometer which connects the target E (fig. 1) with the earth. Knowing the number of rays and the deflexion of the electrometer, we can calculate the deflexion due to one cathode or one positive ray. The result depends upon the nature of the screen used. When the ions are screened off by the electric field, the deflexion due to one positive ray is greater than that due to one cathode ray; when they are screened off by a celluloid film, the deflexion due to a cathode ray is much greater than that due to a positive one. This is, I think, due to the fact that the radiation produced by the positive rays is less penetrating than some of that produced by the cathode ones, so that a much larger proportion of the positive radiation than of the negative is stopped by the celluloid window.

Just as with cathode rays there is a great increase in deflexion when the target is brought forward, so that radiation from it can reach the disk connected with the electrometer; thus the impact of positively electrified particles with metal gives rise to radiation. I showed this by a photographic method many years ago.

The deflexion of the electrometer produced when the target is moved so as to be in sight of the disk connected with the electrometer is in general a larger multiple of the deflexion without the target when the celluloid film is used than with the electrostatic screen. This is, I think, due to the fact that in the latter case the opening through which the rays can pass is a very narrow one while the celluloid window has a much larger area; thus a large proportion of the rays produced by impact with the target will get through the window without any very accurate adjustment of the position of the target, while with the narrow opening only a comparatively small fraction of the rays will get through unless the target is in just the right position.

On the Nature of the Radiation produced by Cathode and Positive Rays.

I have used two methods to investigate the nature of the radiation: the first was to measure the absorption of the metal by thin gold, or aluminium, foil, and the second was to measure the velocity of the electrons ejected from the disk connected with the electrometer when the radiation fell upon it.

Absorption of radiation by thin metallic films.

Films of thin gold and aluminium were interposed in the path of the radiation in the way described in Phil. Mag. xlix. p. 764 (1925), and the consequent diminution in the rate of charging up of the electrometer was measured. Experiments were made on the influence on absorption of the nature of the gases in which the radiation was produced, and of the difference of potential between the anode and cathode of the discharge-tube. The radiations were produced by a stream of cathode rays passing through the gas; as the celluloid window was used, the most absorbable rays were absent. The discharge was produced by a high-potential dynamo made by Evershed and Vignolles, which gave steady potential differences up to 5500 volts.

The thickness of the gold leaf was $7·2 \times 10^{-6}$ cm., of the aluminium leaf $5·3 \times 10^{-5}$.

Absorption of rays by Gold leaf.

Voltage between cathode and anode.	Ratio of intensity of incident to emergent radiation when the cathode rays passed through.		
	Hydrogen.	Oxygen.	Argon.
1500	...	5·0	
2000	3·8	3·5	
2500	...	3·2	
3000	2·6	2·6	2·6
3500	...	2	2·1
4000	2	2	2·0
4500	1·7	2	
5000	2·8 4·0	1·7	1·5
5500	10	1·6	

In hydrogen the current is very unsteady at voltages higher than 4500, and the appearance of the discharge keeps changing abruptly.

Absorption of rays by Aluminium foil.

Voltage between cathode and anode.	Ratio of intensity of incident to emergent radiation when the cathode rays passed through.		
	Hydrogen.	Oxygen.	Argon.
1500	...	2·1	
2000	2·0	1·8	
2500	...	2·0	
3000	1·9	1·6	1·6
3500	...	1·4	
4000	1·4	1·3	1·7
500	1·3	1·3	
000	1·9 2·2	1·4	1·5
5500	8	1·3	

The absorbability of the radiation varies, however, with the kind of electric discharge used to produce it. When an induction coil is used instead of a continuous-current dynamo, the radiation becomes less penetrating even though the length of the equivalent spark-gap may show that the maximum difference of potential produced by the coil is greater than that produced by the dynamo.

We see from the above table that the penetrating power of the radiation generated by the cathode rays increases with the velocity of the rays, though not nearly so quickly as it would if the frequency of the radiation were proportional to the energy of the rays. It does not seem to vary much with the nature of the gas; we shall see, however, that the more absorbable radiations, especially those due to positive rays which cannot penetrate the celluloid film, do vary from one gas to another. The penetrating power of the radiation from the gas was found to be much the same as that of the radiation produced when the same rays were allowed to fall upon a target.

The absorption method of measuring the qualities of the radiation is not applicable to the very easily absorbed radiation which cannot penetrate the thinnest metal foil available, and it is this radiation which is the most important of all in connexion with the theory of electric discharge. I have endeavoured to determine the frequency of this radiation by measuring the velocity of the electrons ejected from a metal plate by the photoelectric action of the radiation. To interpret these experiments it is necessary to consider the theory of the ejection of electrons owing to the photoelectric effects of monochromatic light.

Distribution of energy among the electrons emitted from a plate by photoelectric action.

Let homogeneous radiation fall perpendicularly on a plate of metal, let the mean free path in the metal of the quantum of radiation be λ, then the chance that a quantum is absorbed at a distance between x and $x+\delta x$ from the surface of the metal is proportional to

$$\epsilon^{-\frac{x}{\lambda}}\frac{\delta x}{\lambda}.$$

If all directions of projection of the electron by the quantum are equally probable, the chance that the electron is projected in a direction making an angle between θ and $\theta+\delta\theta$ with the normal to the plate is

$$\tfrac{1}{2}\sin\theta\,.\,\delta\theta\,;$$

hence the chance that an electron should start from between x and $x+\delta x$ in a direction between θ and $\theta+\delta\theta$ is proportional to

$$\epsilon^{-\frac{x}{\lambda}}\frac{\delta x}{2\lambda}\sin\theta\,.\,\delta\theta.$$

If E is the energy of the electron at the beginning of its path through the metal, and E_1 the energy after it has travelled a distance l, we know that

$$E^2-E_1^{\,2}=\beta l,$$

where β is a constant depending upon the metal. If the electron starts from the depth x in a direction θ, the length of its path in the metal will be $x\sec\theta$ and its energy at the end

$$\sqrt{E^2-\beta x\sec\theta}\,.\quad.\quad.\quad.\quad.\quad.\quad.\quad.\qquad(1)$$

The experimental method is to find whether the electron can escape from the metal and reach an electrode parallel to the metal plate against an opposing difference of potential V_0.

If it is to do this, the energy due to the velocity of the electron at right angles to the plate must be not less than V_0e; hence if E is expressed in the form Ve, we must from (1) have

$$\{V^2e^2-\beta x\sec\theta\}^{\frac{1}{2}}\cos^2\theta \not< V_0e\quad.\quad.\quad.\quad.\qquad(2)$$

Putting $V_0=rV$ and $d=V^2e^2/\beta$, this becomes

$$d-x\sec\theta \not< dr^2\sec^4\theta.$$

Hence the chance of an electron being liberated by the light and escaping from the metal is proportional to

$$\frac{1}{2\lambda}\iint\epsilon^{-\frac{x}{\lambda}}\sin\theta\,.\,dx\,.\,d\theta,$$

where the limits of x and θ are found from the equation

$$d-x\sec\theta = dr^2\sec^4\theta.\quad.\quad.\quad.\quad.\quad.\qquad(3)$$

Integrating with respect to x we get the term

$$-\tfrac{1}{2}\Big[\epsilon^{-\frac{x}{\lambda}}\Big]^{d(1-r^2\sec^4\theta)\cos\theta}$$
$$=\tfrac{1}{2}\left(1-\epsilon^{-\frac{d}{\lambda}(1-r^2\sec^4\theta)\cos\theta}\right).$$

Now d is the greatest distance the electron can travel in the metal, and if, as is usually the case, the penetrating power of the radiation is great compared with that of the electrons, d/λ will be small and the preceding expression is approximately equal to

$$\frac{d}{2\lambda}(1-r^2\sec^4\theta)\cos\theta.$$

We have now to find the value of

$$\int \frac{d}{2\lambda}(1-r^2\sec^4\theta)\cos\theta\sin\theta\, d\theta.$$

From equation (3) the limits of θ are 0 and $\cos^2\theta=r$. Using these limits, we find that the value of the integral is

$$\frac{d}{4\lambda}(1-r)^2.$$

Hence the rate at which the electrons escape is proportional to

$$\frac{d}{4\lambda}(1-r)^2.$$

If the energy with which the electrons are liberated by the light quanta is E, and if opposing their escape there is an electric field of potential difference W, and if in addition it requires work measured by P volts to liberate an electron from the metal,

$$r=\frac{\mathrm{W}+\mathrm{P}}{\mathrm{E}}.$$

Hence, if R is the rate at which the electrons escape from the plate,

$$\mathrm{R}=\mathrm{C}\frac{d}{4\lambda}\left(1-\frac{\mathrm{W}+\mathrm{P}}{\mathrm{E}}\right)^2, \quad . \quad . \quad . \quad . \quad (4)$$

where C is a quantity proportional to the intensity of the incident radiation.

Thus the graph representing the relation between R and W is a parabola touching the axis R=0 at the point where W+P=E, while that representing the relation between $\sqrt{\mathrm{R}}$ and W is a straight line.

If the radiation is not monochromatic, then, if the intensity of the radiation having quanta with energies between E and $\mathrm{E}+\delta\mathrm{E}$ is $f(\mathrm{E})\delta\mathrm{E}$, then R, the rate of escape of electrons from the metal when exposed to this radiation, is given by the equation:

$$\mathrm{R}=\int_{\mathrm{W}+\mathrm{P}}^{\infty} f(\mathrm{E})\frac{d}{4\lambda}\left(1-\frac{\mathrm{W}+\mathrm{P}}{\mathrm{E}}\right)^2 d\mathrm{E},$$

$$\frac{d\mathrm{R}}{d\mathrm{W}}=-\int_{\mathrm{W}+\mathrm{P}}^{\infty}\frac{d}{2\lambda}\frac{f(\mathrm{E})}{\mathrm{E}}\left(1-\frac{\mathrm{W}+\mathrm{P}}{\mathrm{E}}\right)d\mathrm{E},$$

and

$$\frac{d^2\mathrm{R}}{d\mathrm{W}}=\int_{\mathrm{W}+\mathrm{P}}^{\infty}\frac{d}{d\lambda}\cdot\frac{f(\mathrm{E})}{\mathrm{E}^2}d\mathrm{E},$$

$$\frac{d^3\mathrm{R}}{d\mathrm{W}^3}=-\frac{d}{2\lambda}\frac{f(\mathrm{W}+\mathrm{P})}{(\mathrm{W}+\mathrm{P})^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Now d and λ are functions of E. We see from equation (1) that d is proportional to E^2, and if we suppose that the absorption of the radiation like that of Röntgen rays is proportional to the cube of the wave-length, λ varies as E^3. On these assumptions,

$$\frac{d^3\mathrm{R}}{d\mathrm{W}^3} \text{ varies as } -\frac{f(\mathrm{W}+\mathrm{P})}{(\mathrm{W}+\mathrm{P})^3}.$$

Thus if we determine by experiment the way R varies with W and draw the graph, we can get from it the distribution of the different types of radiation in the incident light; the place where R vanishes will give the greatest frequency occurring in the radiation. If the curve is a parabola the radiation is homogeneous with this frequency, if it is not a parabola the radiation is not homogeneous; the distribution of the intensities can be determined by the preceding equation.

We have assumed that when an electron receives energy from a quantum of light it is as likely to start in any one direction as in any other. The justification for this is the shape of the graphs obtained by experiments.

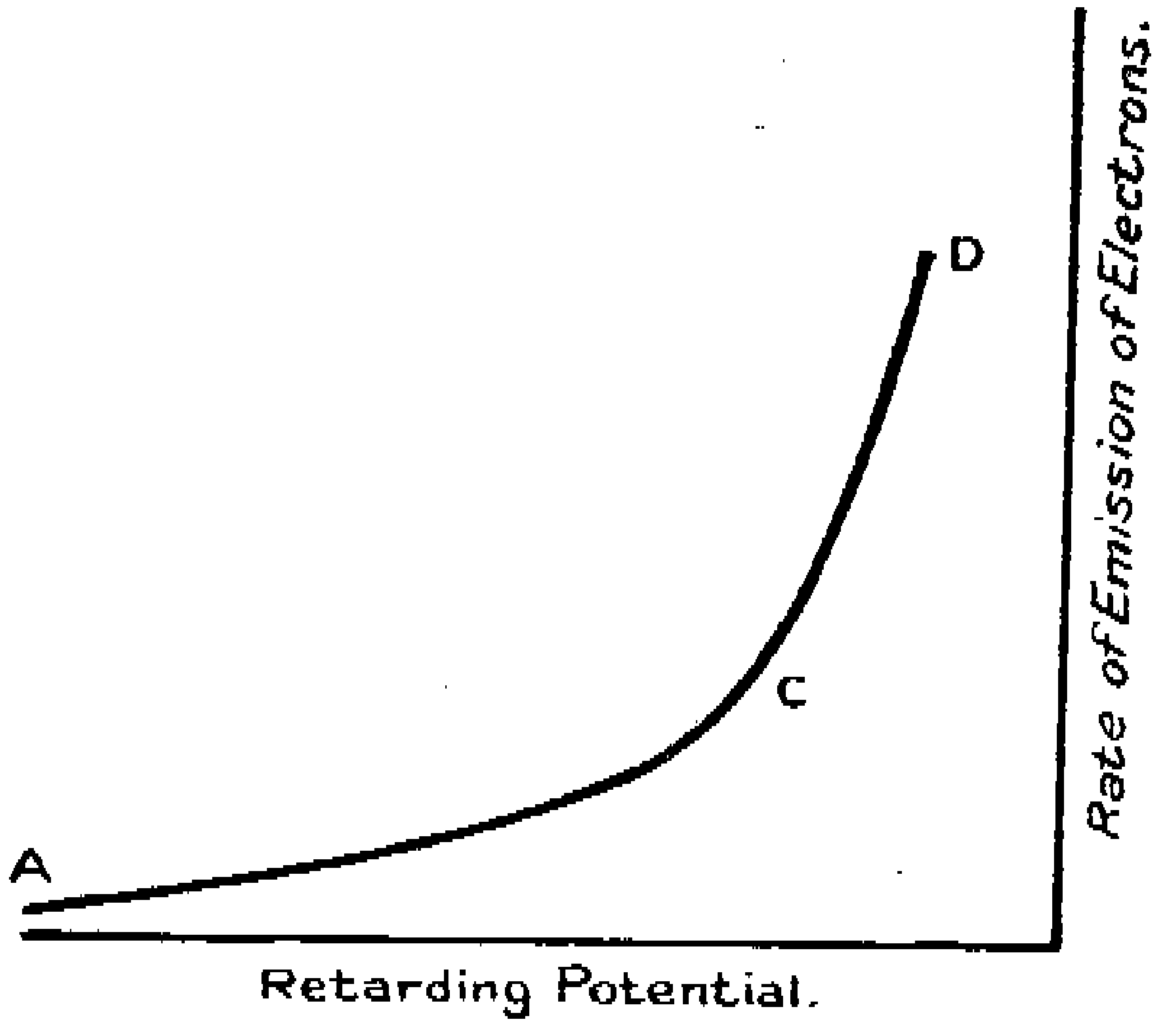
Along any parabola whose axis is parallel to the axis of y, d^2y/dx^2 is constant and d^3y/dx^3 is zero. Hence we infer from equation (4) that when the graph (fig. 3) for the relation between the rate of emission of the electrons and the retarding potential can through a considerable stretch CD be represented by a single parabola, there is no radiation in the tube whose energy quantum is between the values of W at C and D. This gives a convenient method of determining the character of the radiation from the shape of the graph.

Thus, to take an example, if AD represents the graph, and if AC is one parabola and CD another, we know that the radiation in the tube will be of two types—one having a quantum equal to W_A+P, and the other to W_C+P, where W_A and W_C are the retarding potentials at A and C respectively, and P is the work required to extract an electron from the metal.

The relation between the rate of emission of electrons and the retarding potential will depend upon the shape of the illuminated electrode and the disposition of the retarding electric field. In our experiments the illuminated electrode was a flat plate and the retarding electric field was that between two parallel plates. If the retarding electric field had been, as in Prof. Richardson's experiments (Phil. Mag. xxiv. p. 575, 1912), that between a large sphere and a small illuminated electrode placed at its centre, then an electron could escape if its total kinetic energy, and not necessarily that part of it due to motion in a particular direction, exceeded rE, and the relation (2) would be replaced by

$$\{E^2-\beta x\sec\theta\}^{\frac{1}{2}} > rE.$$

Fig. 3.



Using this relation instead of (2), we find that the rate of emission of electrons is proportional to

$$\begin{aligned}&\frac{d}{\lambda}(1-r^2)\\ =&\frac{d}{\lambda}\left(1-\left(\frac{W+P}{E}\right)^2\right) \quad (\alpha),\end{aligned}$$

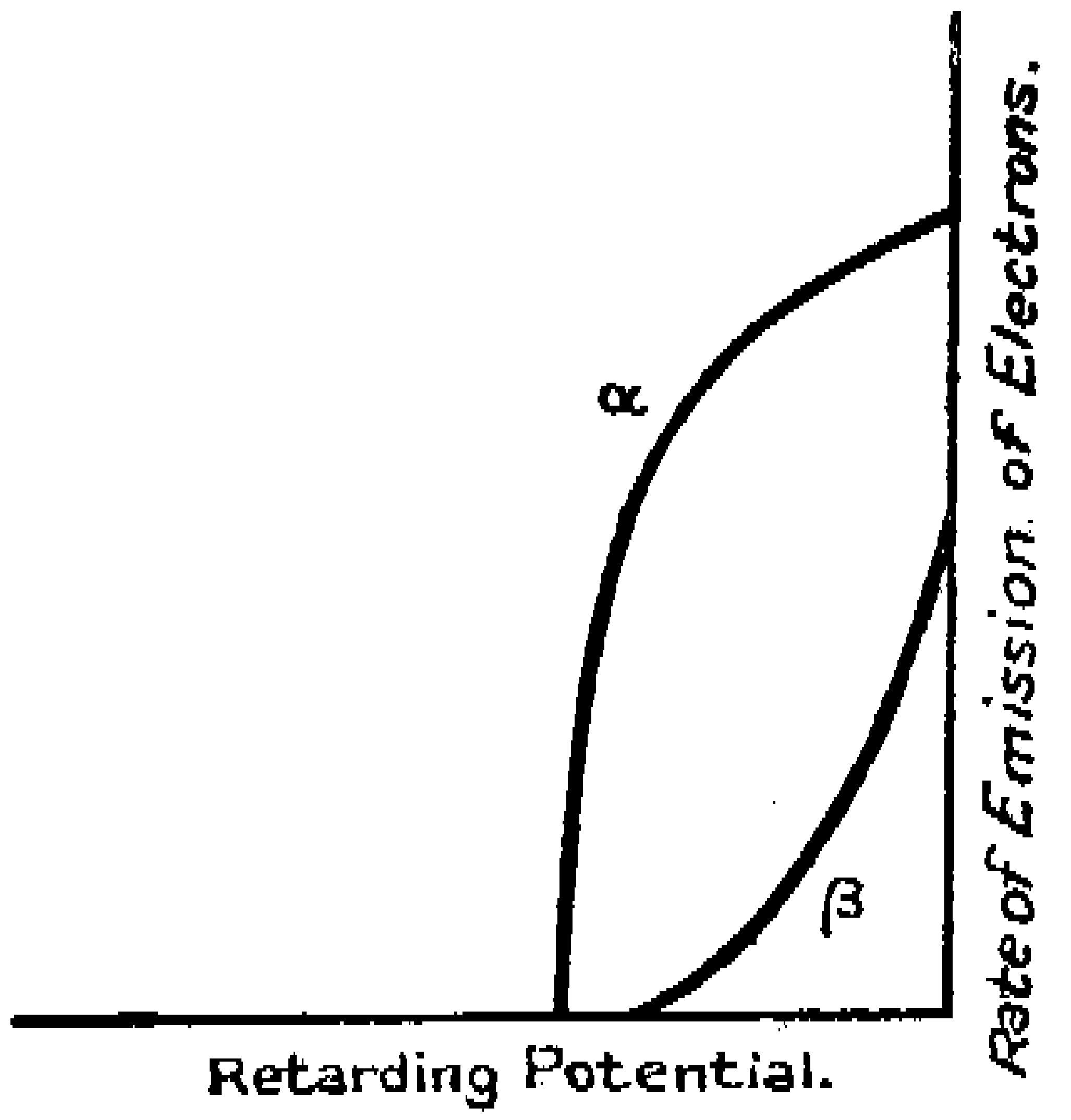
instead of, as in our case,

$$\frac{d}{\lambda}\left(1-\frac{W+P}{E}\right) \qquad (\beta).$$

The graph represented by α is also a parabola, but it is of the type shown in fig. 4 (α), while the graph for β is represented by fig. 4 (β).

With the relation α the slope of the graph vanishes when $r=0$ and is greatest when $r=1$, while with the graph β the slope vanishes when $r=1$ and is greatest when $r=0$.

Fig. 4.



If the radiation were heterogeneous the slope of the α-graph would vanish when $r=0$, though it would not necessarily be greatest at the place on the graph where emission vanished. For the β graph for heterogeneous radiation the slope would vanish when the emission vanished and would be greatest when $r=0$. The graphs in my experiments are always of the β type, and what I think is significant is that though in the majority of cases the graph cannot be represented by a single parabola, there are a few cases, one of which is the radiation given out by the glow next the anode in the discharge through pure oxygen, where the approximation to the parabolic form is very close. This is what we should expect if the radiation were in general heterogeneous, but there are special cases in which it is approximately homogeneous.

Experiments to determine the Distribution of Energy in the electrons emitted by the photoelectric effect of the radiation.

The arrangement used is shown in fig. 2. D is the disk connected with the electrometer by the insulated rod R; this rod is surrounded by a metal tube connected with the earth to shield off electrostatic effects from the disk and its connexions. In front of the disk and parallel to it is a sheet of wire gauze turned back at the ends as in the figure, so as to surround the disk with an equipotential surface When the ends were not turned back I found the results depended to some extent on the distance between the plane of the gauze and that of the disk. I attribute this to some of the electrons escaping through the gap between the gauze and the disk without coming under the influence of the retarding potential. The wire gauze was connected with a battery of storage cells, and differences of potential ranging up to 400 volts could be established between the gauze and the disk; if the gauze were negative with respect to the disk the electric field tended to stop, if it were positive to promote the emission of electrons. The rates of emission of electrons for a series of potential differences were measured by finding the deflexion of the electrometer due to the exposure of the disk to the radiation for a fixed time. The readings with the same difference of potential between the gauze and the disk were fairly constant when the conditions were good, even when the radiation came from a discharge produced by an induction coil. To standardize the readings, the deflexion when there was no potential difference between the gauze and the disk was measured at frequent intervals.

When the coil was working well the deflexions of the electrometer were fairly constant with similar conditions. These investigations, however, brought to light a striking feature of the radiations produced by the discharge: the character of the radiation may change quite abruptly, sometimes without any appreciable change in the appearance of the discharge. I think these changes are due to gases coming off the walls of the tube or to incursions of mercury vapour; later on, experiments are described which show that when heavy gases are introduced into the tube radiations of much higher frequency are added to those already in the tube.

In order that the discharge should be able to pass through the tube the pressure must not be too low; in the great majority of these experiments the pressure was above 01 mm. of Hg, and was thus much higher than that occurring in recent experiments on photoelectric action.

In my experiments a considerable increase in the emission of electrons was produced by putting an accelerating potential on the gauze—*i. e.*, the emission was greater when the gauze was positive to the plate than when the gauze and plate were at the same potential.

Another effect frequently observed was that when the gauze was strongly negative to the plate, the plate not merely ceased to lose electrons when exposed to the radiation but slowly acquired a negative charge. The effect was small and soon showed saturation, *i. e.* the rate of increase of the negative charge soon becomes independent of the difference of potential between the gauze and the plate.

This effect might occur if the gas between the gauze and the plate were ionized by the radiation so that a current of negative electricity passed from the gauze to the plate; it would also occur if some of the radiation were reflected from the disk on to the wires of the gauze so that these gave out electrons by photoelectric action. There are, however, grave difficulties in accepting one or both of these explanations. If the effect were due to the ionization of the gas, then it would increase with the amount of gas surrounding the disk and exposed to the radiation. The apparatus was designed to make this as small as possible, and when the position of the gauze was altered so that the distance between it and the disk was increased and therewith the amount of ionizable gas, the negative effect diminished instead of increasing. Again, if it were due to the reflected radiation it ought to diminish if the surface of the metal in the wire gauze is diminished. I tried the effect of replacing one piece of gauze by another made of much finer wire and more open mesh, but I could not detect any diminution in the negative effect.

The experiments seem to me to indicate that there is at the surface of the disk a layer of ionized gas containing positive as well as negative ions, and that when the gauze is very strongly negative some of the positive ions are pulled out of this layer, so that the disk gets a negative charge. The existence of this retrograde current has to be taken into account in interpreting the graphs, for when the disk neither gains or loses a positive charge it does not necessarily follow that the flow of electrons from it has completely stopped; it may be that there is still a small flow from the disk which is just balanced by the retrograde current, so that E, the energy given to an electron by the light quantum, will be somewhat greater than the value given by the equation

$$E = W + P,$$

where W is the retarding potential when the disk neither gains nor loses an electric charge.

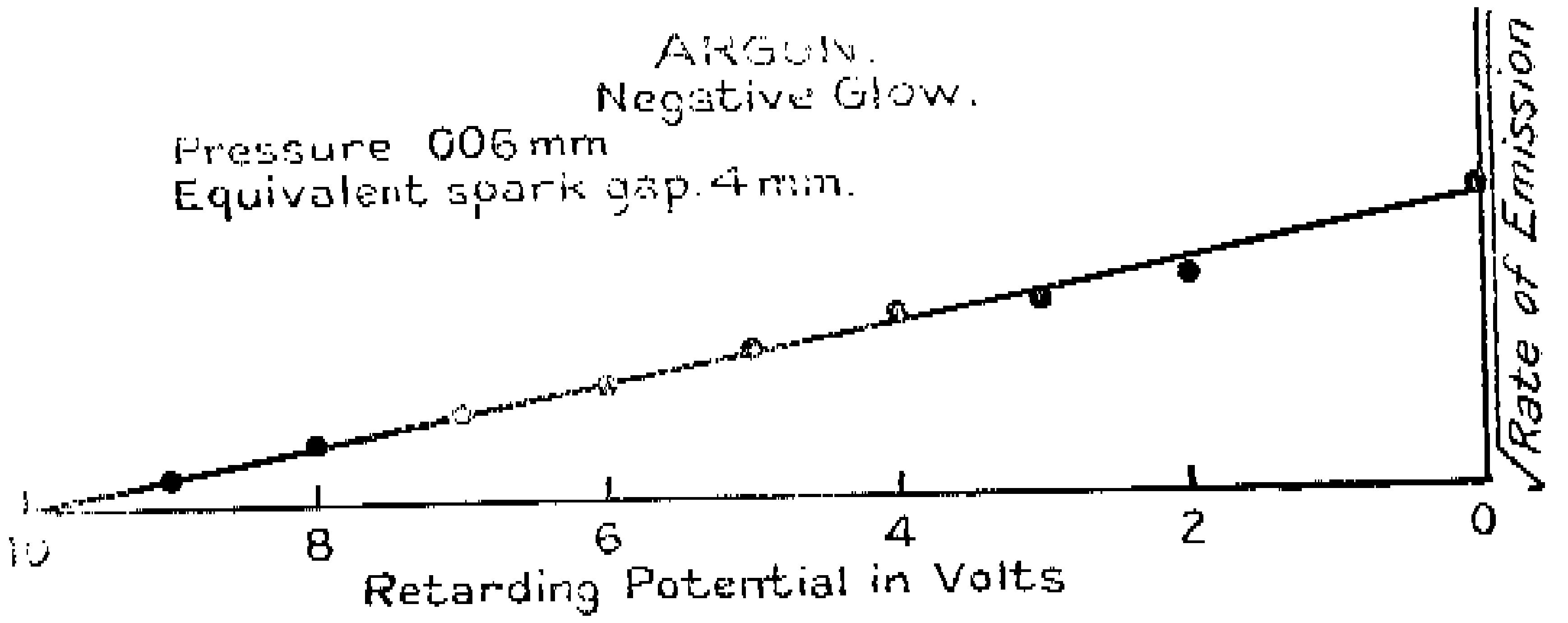
The retarding potential was got from a potentiometer consisting of 100 resistance coils placed in series. The electromotive force on the potentiometer was provided by a battery of small storage cells. To allow for possible variations in the induction coil, readings of the deflexion of the electrometer when there was no retarding potential were taken between those for the different retarding potentials. A convenient way of detecting changes in the character of the radiation is to apply by means of the potentiometer a retarding potential which reduces the flow of electricity to the disk to zero. When the coil is working well, it is possible to get so good a balance that there is not a deflexion of one division on the scale of the electrometer in several minutes. This balance often remained undisturbed when the pressure of the gas in the discharge-tube was altered and with it the potential difference between the electrodes, showing that the limiting radiation did not change appreciably with the physical conditions but was determined by the nature of the gas. If when it is in this state the liquid-air traps which have been used to take out impurities be removed, the balance will suddenly change and it will require a larger retarding potential to stop the flow of the electrons from the illuminated disk, showing that a radiation of a harder type has been introduced, probably arising from the heavier molecules liberated by the removal of the liquid air. This explanation is supported by the fact that the change in the retarding potential required to stop the emission is much more marked than the change in the rate of emission when no retarding potential is applied; this would be the case if a small quantity of radiation of a harder type were produced by some impurity in the gas.

Discussion of the Experiments.

A large number of experiments on the relation between R, the rate of emission from the illuminated copper disk, and W, the retarding potential, were made and the results analysed to find the nature of the radiation. In some cases examples of which are given below, the whole of the graph could be very approximately represented by a single parabola, so that when $\sqrt{R}$ was plotted against W the result was a straight line. Examples of this are given in figs. 5, 6, and 7.

Fig. 5 is for the radiation from the negative glow in argon, the pressure was ·006 mm., the discharge was produced by an induction coil and the equivalent spark-gap was 4 mm. It will be seen that the graph for $\sqrt{R}$ and W is very approximately a straight line and that the emission vanishes when W = 10 volts; thus E, the quantum of energy in the radiation, will be given by

Fig. 5.



$$E = 10 + P + \text{a correction due to the retrograde current.}$$

Taking W as 3·5 volts, this makes the quantum somewhat greater than 13·5 volts.

Fig. 6.

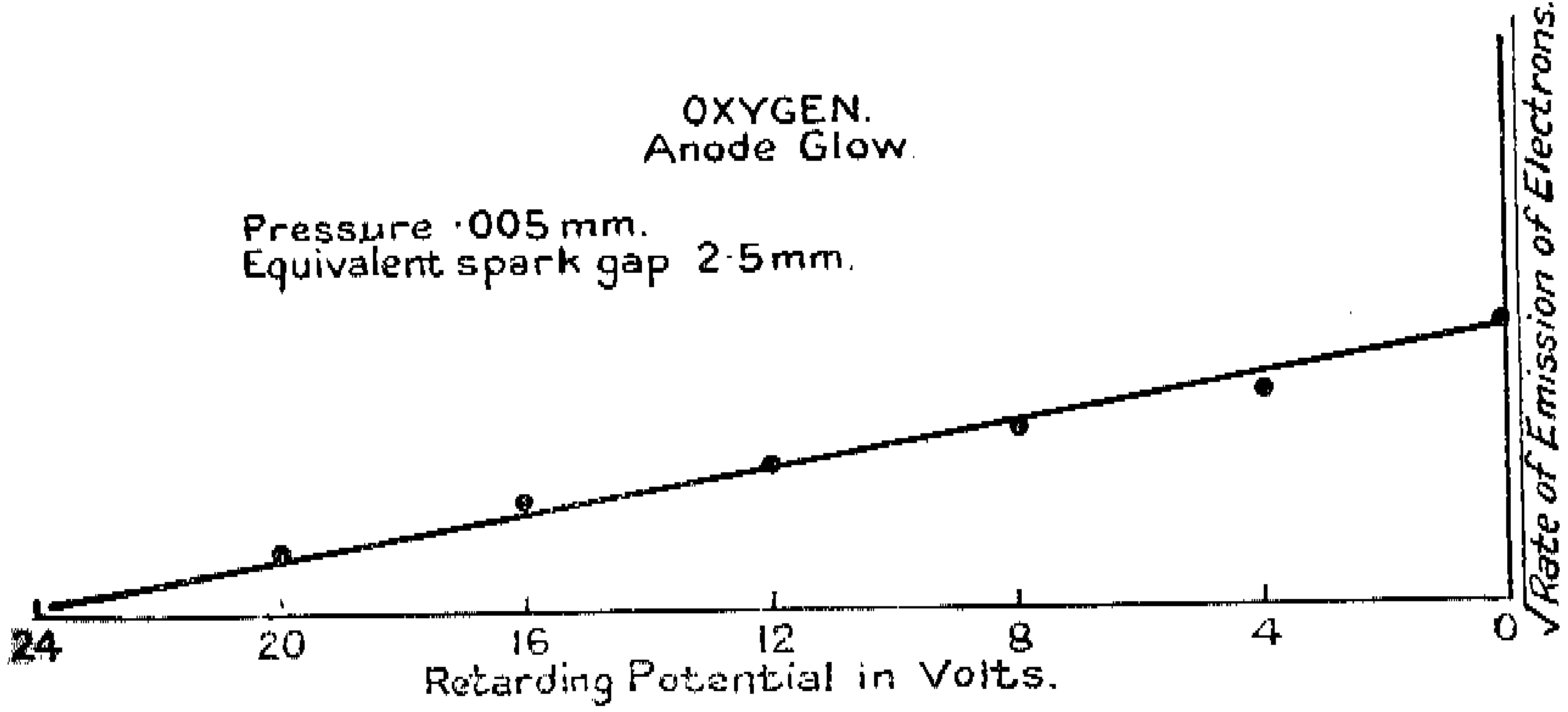


Fig. 6 is the graph for $\sqrt{R}$ and W for the radiation from the anode glow in oxygen at a pressure of ·005 mm.; the discharge was produced by an induction coil and the equivalent spark-gap was 2·5 mm. Again the radiation is approximately homogeneous, and the emission vanishes when the retarding potential is 24 volts.

Fig. 7 is the graph for the negative glow in oxygen when the discharge was produced by a continuous-current dynamo; the potential difference was 400 volts and the current through the tube 2·6 milliamperes, the pressure was ·045 mm.; the emission is stopped by a retarding potential of 12 volts, so that the quantum of radiation is considerably less than in the preceding case.

It is only, however, in exceptional cases that the graph for $\sqrt{R}$ and W is a straight line throughout the whole of its length; it much more frequently happens that the results for the higher retarding potentials are approximately on a straight line, while those for the smaller ones are far from the prolongation of this line.

Fig. 7.

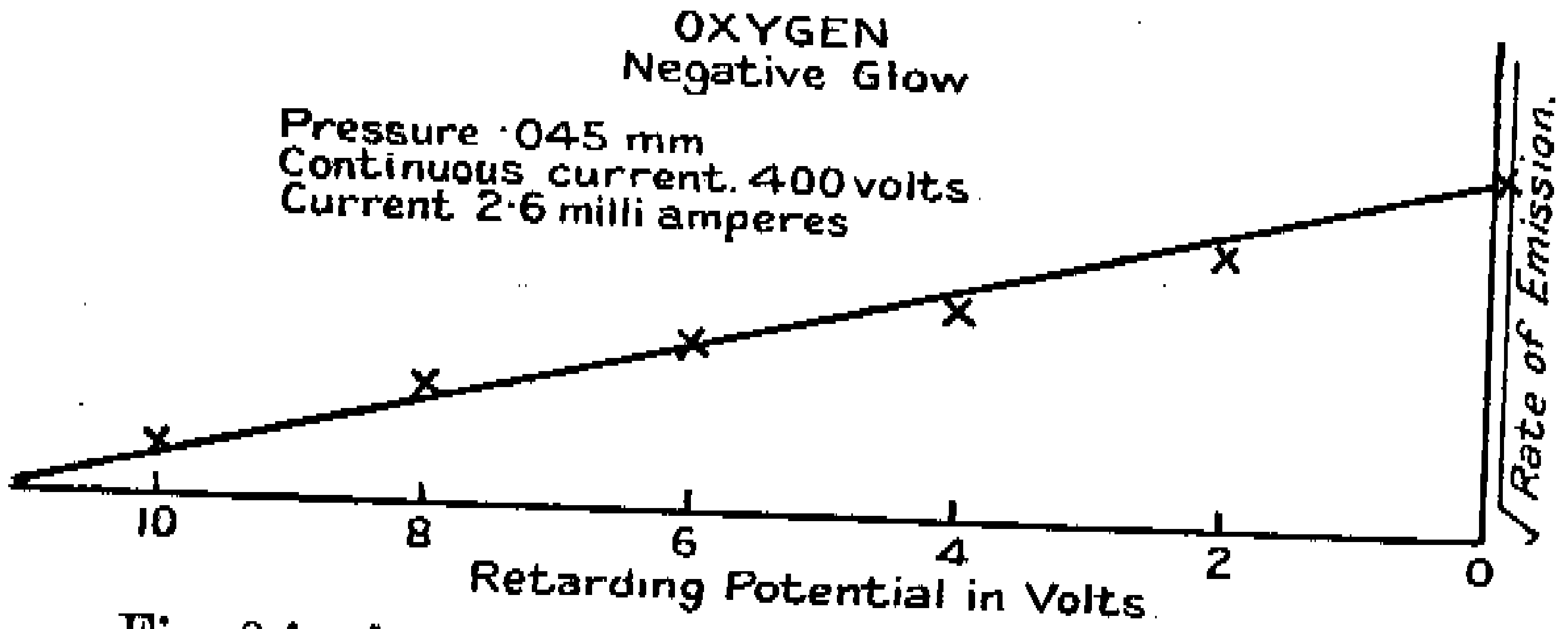


Fig. 8 is the graph representing the relation between R and W for the radiation from the negative glow in the discharge produced by an induction coil through hydrogen at the pressure of ·01 mm. of mercury; the equivalent spark-gap was 4 mm. The unbroken line represents the observations, the dotted lines the two parabolas

$$y = \frac{26\,(10-\mathrm{W})^2}{100}$$

and $$y = \frac{12\,(2-\mathrm{W})^2}{4};$$

the sum of the ordinates of these is not distinguishable from the graph on the scale of the diagram. We conclude from this that the radiation was concentrated in two types, one having the energy quantum equal to 10 + P, and the other a radiation of a much softer type with the energy quantum equal to 2 + P.

Fig. 8.

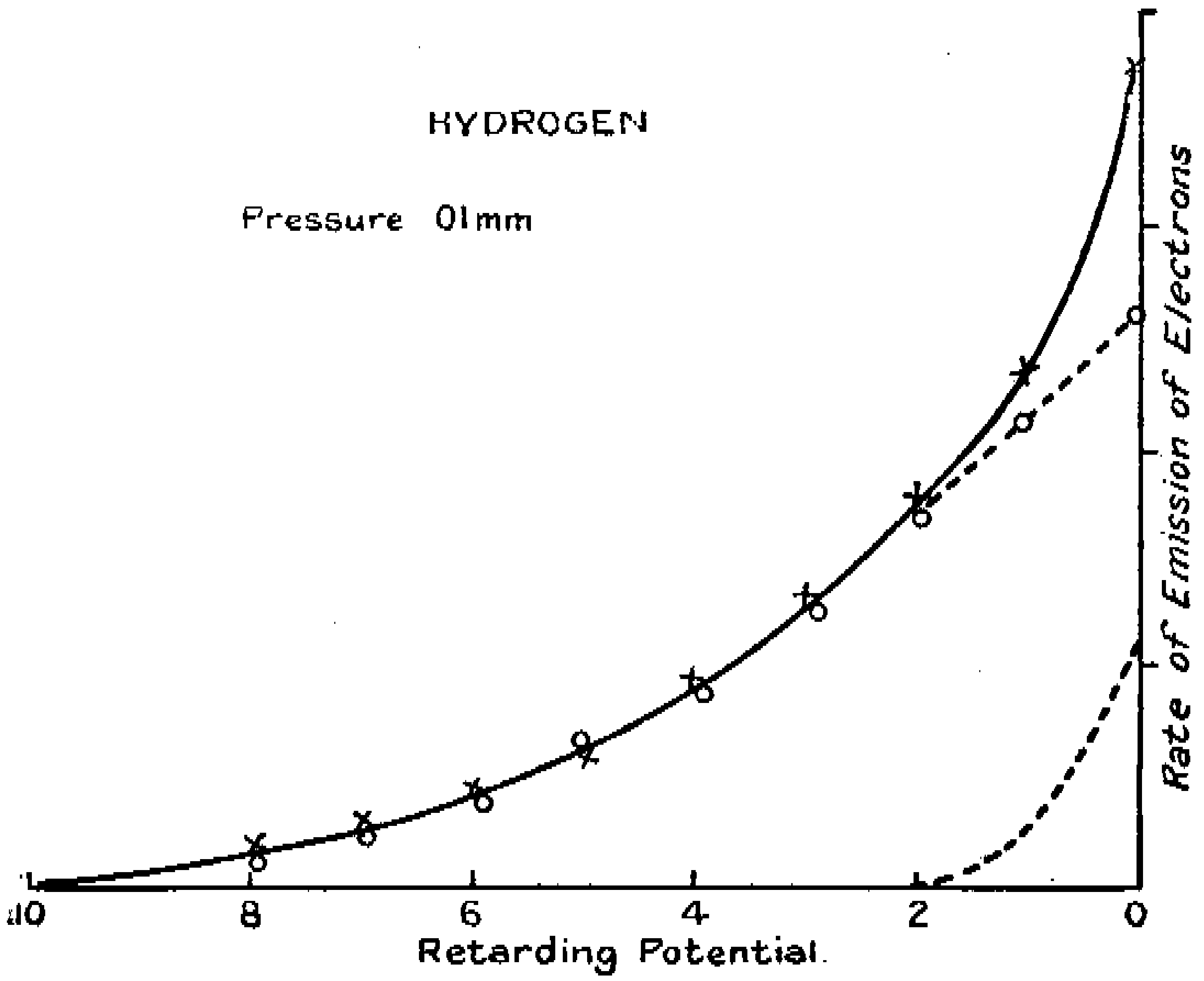


Fig. 9.

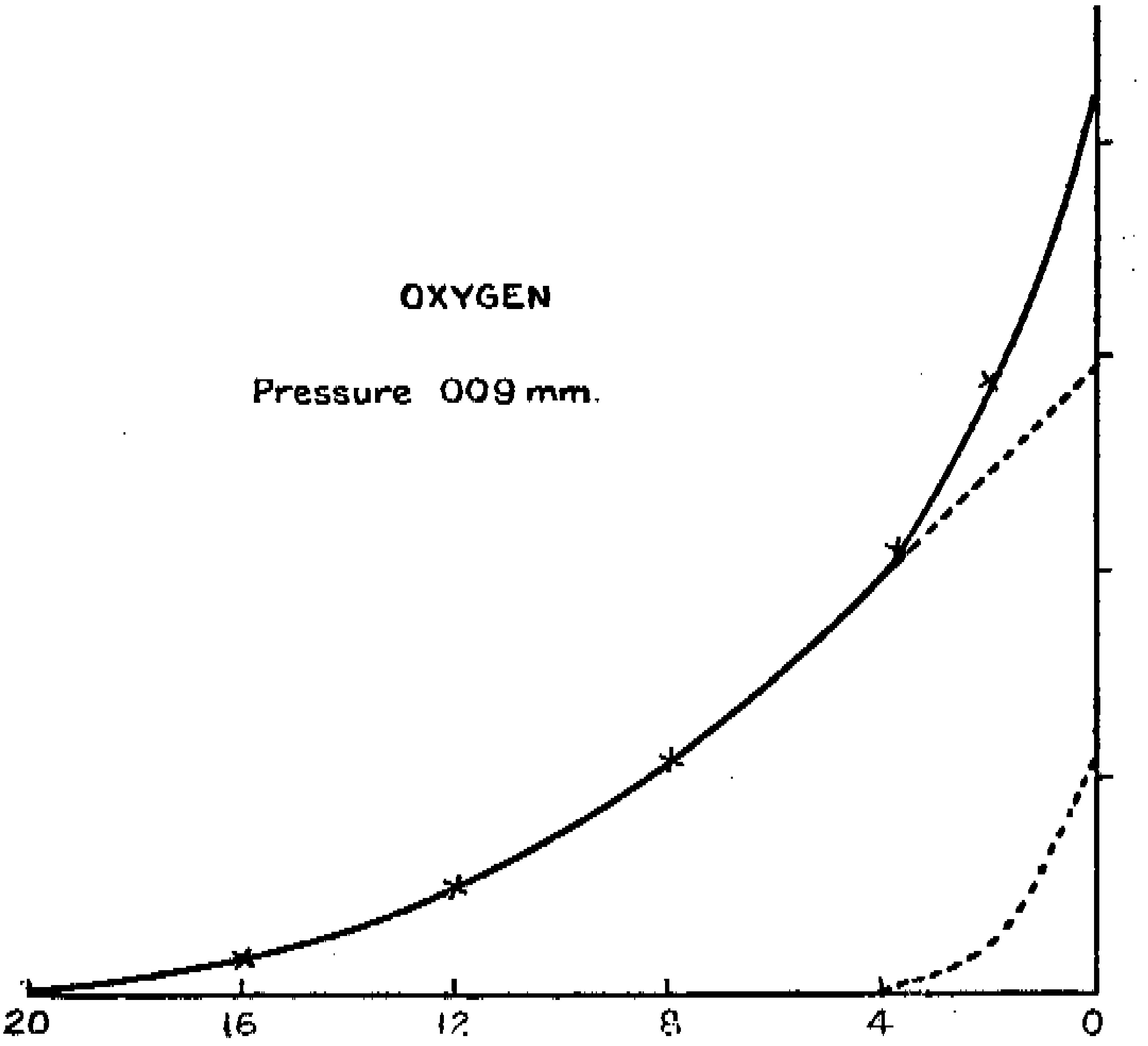


Fig. 9 is the graph representing the radiation from the negative glow in the discharge through oxygen at the pressure ·009 mm. of mercury produced by a large induction coil; the equivalent spark-gap was 4·0 mm.

The graph can be represented by the superposition of the two parabolas

$$R = \frac{39}{256}(20-W)^2,$$

$$R = \frac{25}{16}(4-W)^2.$$

This implies that the radiation consists in the main of two constituents, one having for energy quantum 20+P volts, and the other 4+P volts.

The graphs for the radiation from the negative and anode glows were obtained by using a piece of gauze placed in front of the window through which the radiation passed on its way to the disk connected with the electrometer as the cathode or anode for the electric discharge. With this arrangement the deflexions of the electrometer were very large, and capacities sometimes as large as ·1 microfarad had to be connected to the electrometer to reduce the deflexion to measurable dimensions. The illuminated disk was in this case receiving radiations of the same kind as those which fall on the metal surface of the cathode or anode of the discharge-tube, and as the disk emits copious streams of electrons, it follows that both the anode and cathode in the discharge-tube receive radiation which induces a copious emission of electrons. This emission at the cathode gives rise to the high-speed cathode-rays; while the emission at the anode proceeds until the electrons accumulate in front of the anode in sufficient density to produce a retarding potential sufficient to stop the flow of the electrons. This potential must be equal to that found in the experiments we have just described. The existence of an anode fall of potential was proved many years ago by Skinner, and the magnitude of it was found to be in the neighbourhood of about 20 volts with variations of a few volts depending on the gas in the tube and the nature of the anode. It is thus of the same order of magnitude as the retarding potential necessary to stop the flow of electrons measured in the preceding experiments.

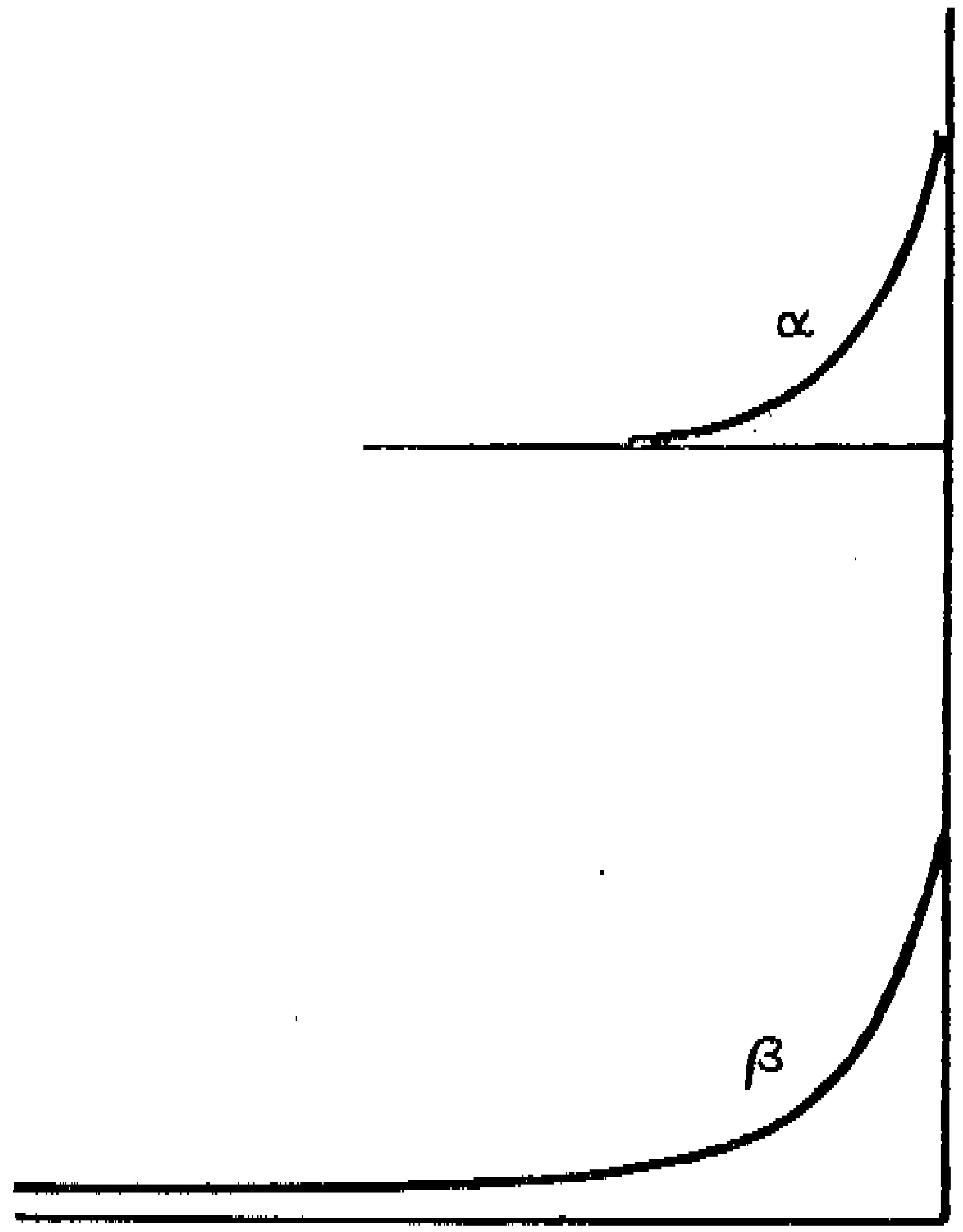
To test whether the effect observed in these experiments was wholly due to radiation coming from the tube and not in part due to uncharged atoms or molecules in an excited state making their way through the screen and then giving out radiation, the disk connected with the electrometer was placed in a side tube so as to be out of the way of radiation

from the tube, and by means of a pump a constant stream of gas was drawn from the discharge-tube past the disk: there was, however, no deflexion of the electrometer.

Radiation produced by the passage of Cathode and Positive Rays through Gases.

I have investigated the radiation produced when cathode and positive rays pass through hydrogen, helium, and argon. When the pressure is not lower than ·01 mm. the graphs for the radiation from the cathode and positive rays are not very different; they all showed that the emission of electrons was stopped by retarding potentials which rarely exceeded 12 volts. The analysis of the graphs showed that the radiation was by no means homogeneous. The radiation produced when the positive rays struck against metals gave graphs similar to those due to the radiation produced by the passage of positive rays through the gas. At very low pressures when the potential difference between the anode and cathode is large, there is a distinct difference between the graphs for the radiations from the positive and cathode rays. The graphs for the positive rays are similar to those at the higher pressures and are of the type shown in fig. 10 α, while the

Fig. 10.



graph for the radiation from the cathode rays is of the type of fig. 10 β.

In both cases we have on the application of a small retarding potential a rapid fall in the rate of emission of electrons. With cathode rays, however, this initial rapid fall is succeeded by a stage where the deflexion diminishes only slowly with the retarding potential, and there may be an appreciable emission with a retarding potential as great as 100 volts. With the radiation from the positive rays we have only the stage represented by the rapid fall at the beginning, the emission vanishes when the retarding potential is only a few volts. This indicates that in the radiation from the cathode rays we have a mixture of soft radiation with quanta represented by a few volts with much harder radiation whose quanta may be comparable with a hundred volts. With the positive rays the radiation is all of the softer type.

The production of ionizing radiation by positive rays passing through a gas or striking against a solid has an important bearing on the question of whether or not positive particles ionize by collision. Ionization by positive particles has been observed and measured by Pavlow (Proc. Roy. Soc. A, xc. p. 898, 1914) and others, and has been interpreted as a proof that such particles as well as electrons produce ions by collision. There are, as I have pointed out, very serious theoretical objections to this view, and such results as have been obtained may be explained as due to the radiation emitted by the particles. This radiation will give rise to the emission of electrons from the molecules of the gas and from the surfaces of solids in the discharge-tube, and it is to this and not to direct collisions that we ascribe the ionization observed by Pavlow.

There is still very much that is obscure about the ionization due to positive rays. Seeliger (*Physik. Zeit.* xii. p. 839, 1912) has made quantitative experiments on the subject, and these indicate that the total number of ions produced by a positive ray is but small, very far below the number which would exhaust the kinetic energy of the ray; he found that the number does not vary much either with the speed of the ray or with the pressure of the gas. These results would follow if the ionization were due not to the energy of translation of the particle but to energy internal to the particle, such as might be represented by supposing the particle to contain a limited number of undischarged quanta of radiation, and that it is these, and not the translational energy of the particle, which produce the ionization.

The Electrodeless Ring Discharge.

A copious and convenient source of radiation of the type we are studying is supplied by the electrodeless ring discharge.

When a solenoid is placed in the circuit connecting the outer coatings of two Leyden jars, whose inside coatings are connected with the terminals A, B of an induction coil, when sparks pass between these terminals electrical oscillations are excited and the solenoid is traversed by rapidly alternating currents. If a glass vessel containing gas at a low pressure is placed inside the solenoid, the rapidly alternating currents in the solenoid will by electromagnetic induction produce in the vessel closed lines of electromotive force, and these when the pressure of the gas inside is low produce a ring discharge which is often exceedingly bright. The study of the radiation given out by this discharge has led to some interesting results.

The arrangement adopted was as follows: the solenoid was placed over the tube C in fig. 1 so that the ring discharge is well in sight of the disk used to test the photoelectric effect due to the radiation. Measurements were made on the rate of emission under different retarding potentials. The results seemed to depend to a great extent upon the purity of the gas. With very pure helium or hydrogen a retarding potential of about 12 volts was sufficient to stop the emission of electrons from the illuminated disk, while for oxygen a potential difference of about 24 volts was required. The magnitude of the limiting potential did not seem to vary with the pressure of the gas or the frequency of the discharge. The analysis of the graphs showed that the radiation was not homogeneous. Not infrequently, however, abrupt changes took place in the retarding potential required to stop the emission of electrons, and instead of 12 volts being sufficient, in some cases more than 100 volts were required.

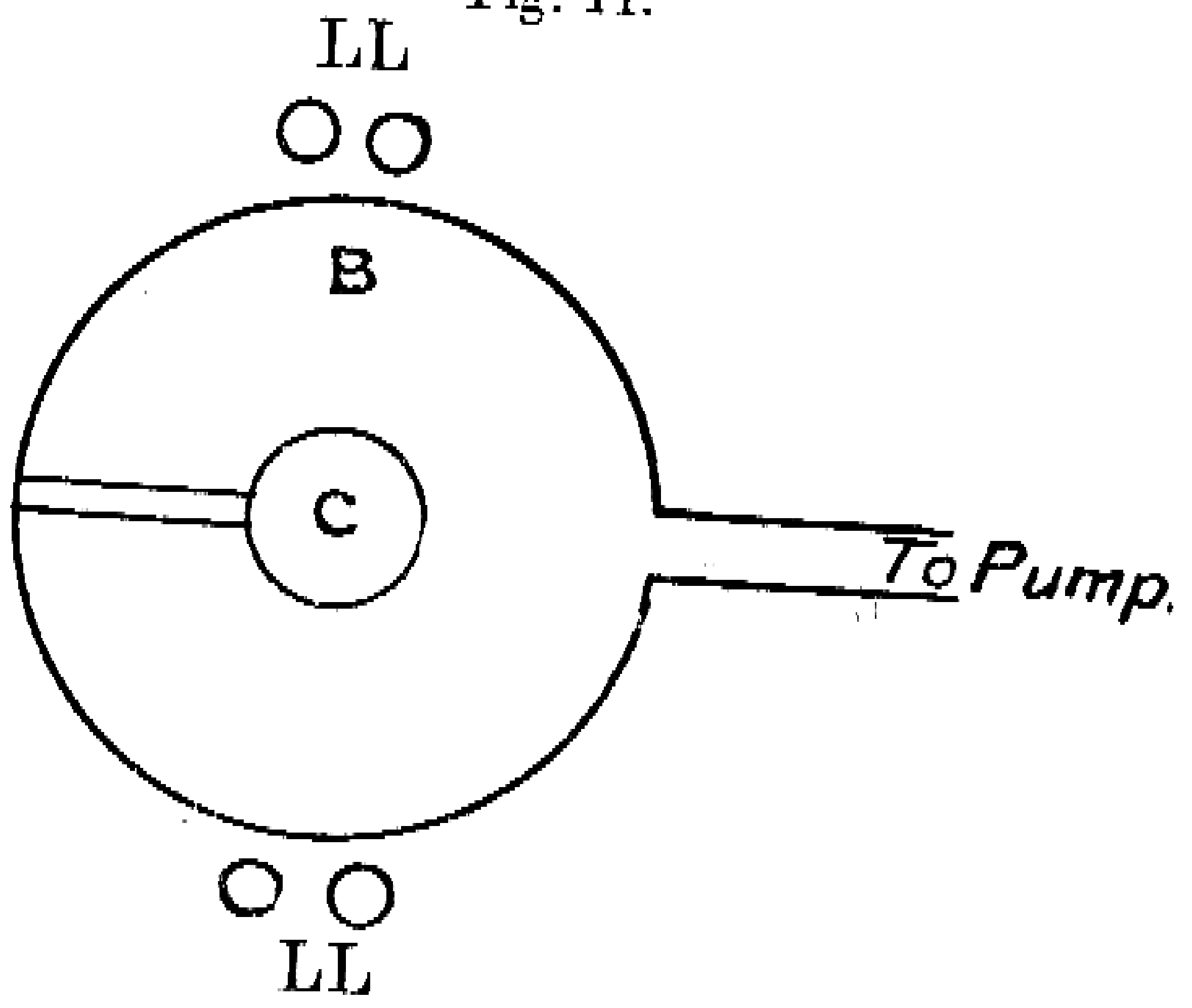
These changes sometimes occurred spontaneously; they could generally be brought about by removing the liquid-air trap used to free the gas from mercury vapour. Though the change in the limiting potentials may be great, there is not a correspondingly large change in the rate of emission of the electrons when there is no retarding potential. It would seem as if the effect were due to the presence of an impurity which emits a much harder type of radiation than that coming from the pure gas.

Radiation from dark electric discharge.

The luminous rings characteristic of the electrodeless discharge appear only when the pressure of the gas is within somewhat narrow limits; but even at pressures lower than those where the luminous radiation appears the electrometer gives large deflexions showing the existence of radiation of smaller wave-lengths than those of visible light. The analysis of this radiation by the method of the retarding potential shows that it is mainly in the region of the radiation which has a quantum of the order of the ionizing potential of the gas.

The following experiment supplies direct evidence of the existence of currents through the gas even when there is no luminosity.

Fig. 11.



C is a bulb containing gas at a pressure at which the luminous discharge is very bright, it is placed inside another bulb B connected with a pump. The coils L L for producing the electrodeless discharge are placed outside B. When the gas in B is at atmospheric pressure there is a bright ring discharge in C; but when the pressure is reduced so that the ring discharge appears in B, that in C disappears. The gas in B is a conductor of electricity and the currents induced in it shield off from C the effects due to the currents through the coils L L. When the pressure in B is reduced so that the vacuum in B is a very high one, the bright ring discharge appears again in C: the induced currents through B are not now sufficient to shield off the effects of the primary current. There is, however, a considerable range of pressure in which, though there is no visible discharge in B, that in C is stopped; showing that there are sufficient currents passing through B without exciting visible luminosity, to shield off the effects of the primary currents. As there would be but little shielding unless the currents passing through the gas were comparable with those which pass through the coil, this experiment shows that large currents may pass through the gas under certain conditions without exciting visible luminosity, though, as we have seen, they do excite radiation of smaller wave-length.

The following calculation shows that when the effect of the primary coil is shielded by the currents in the rarefied gas, a large number of electrons must be present in the gas.

Let us suppose that the coil is a long straight solenoid; consider the free motion of an electron in an exhausted tube coaxial with the solenoid. Let r, θ, z be the cylindrical coordinates of an electron, z being measured parallel to the axis. Then, if H is the magnetic force due to the currents in the solenoid and gas, the electric force at a point distance r from the axis is $\frac{r}{2}\frac{d\mathrm{H}}{dt}$ and is tangential. Hence the equations of motion of a free electron are

$$m\frac{1}{r}\frac{d}{dt}\left(r^2\frac{d\theta}{dt}\right)=\left\{\frac{1}{2}r\frac{d\mathrm{H}}{dt}+\frac{\mathrm{H}\,dr}{dt}\right\}e, \quad . \quad . \quad (1)$$

$$m\left(\frac{d^2r}{dt^2}-r\left(\frac{d\theta}{dt}\right)^2\right)=-\mathrm{H}er\frac{d\theta}{dt}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where m is the mass, and e the charge on an electron.

The first of these may be written in the form

$$\frac{d}{dt}\left(r^2\frac{d\theta}{dt}\right)=\frac{e}{2m}\frac{d}{dt}(\mathrm{H}r^2),$$

$$r^2\frac{d\theta}{dt}=\frac{e}{2m}\cdot\mathrm{H}r^2+\mathrm{C};$$

if $d\theta/dt$ and H both vanish when $t=0$,

$$r^2\frac{d\theta}{dt}=\frac{e}{2m}\mathrm{H}r^2$$

or $$\frac{d\theta}{dt}=\frac{e}{2m}\cdot\mathrm{H}.$$

The velocity of the electron at right angles to r is thus

$$\frac{e}{2m}r\mathrm{H};$$

and if ρ is the density of the electrons, the current per unit length of the gas

$$\frac{e^2}{2m}\int_0^a \mathrm{H}\rho r\,dr,$$

where a is the radius of the tube. If N is the number of electrons contained between two planes at right angles to the axis of the tube and unit distance apart,

$$\int_0^a \rho\,.\,r\,.\,dr=\frac{\mathrm{N}}{2\pi};$$

thus the currents through the gas are less than

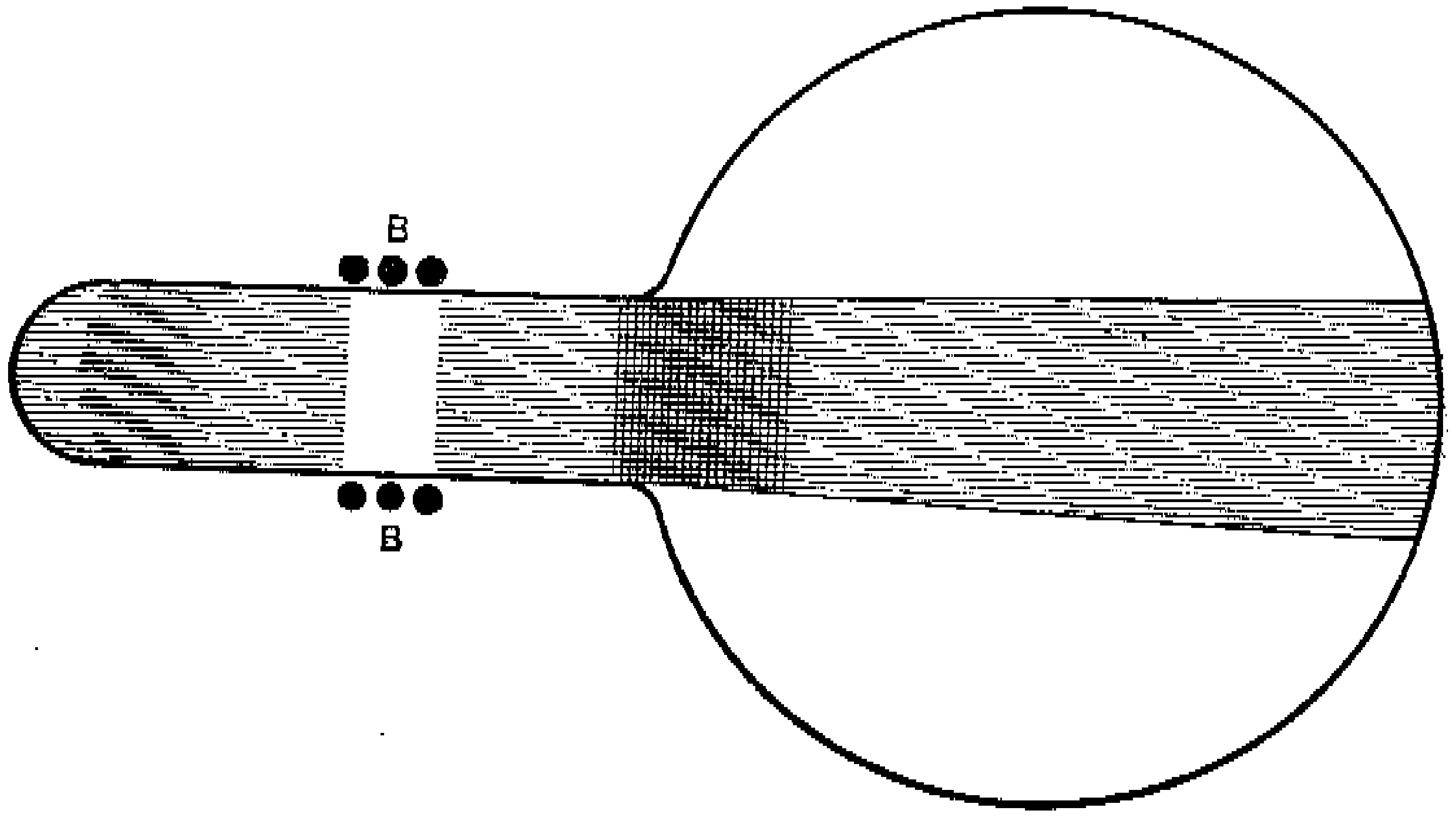
$$\frac{e^2\mathrm{NH}_0}{4\pi m}.$$

where H_0 is the value of H when $r=a$, if c is the current through unit length of the solenoid,

$$\mathrm{H}_0=4\pi c;$$

hence the current through the gas is less than $\mathrm{N}e^2/m$ times the current through the coil. If the current through the gas is to neutralize the effect of that through the coils, the magnitude of the gaseous current must not be less than that through the coils, hence $\mathrm{N}e^2/m$ must not be less than unity, since e^2/m is $2{\cdot}8\times10^{-13}$, N must not be less than $3{\cdot}6\times10^{12}$.

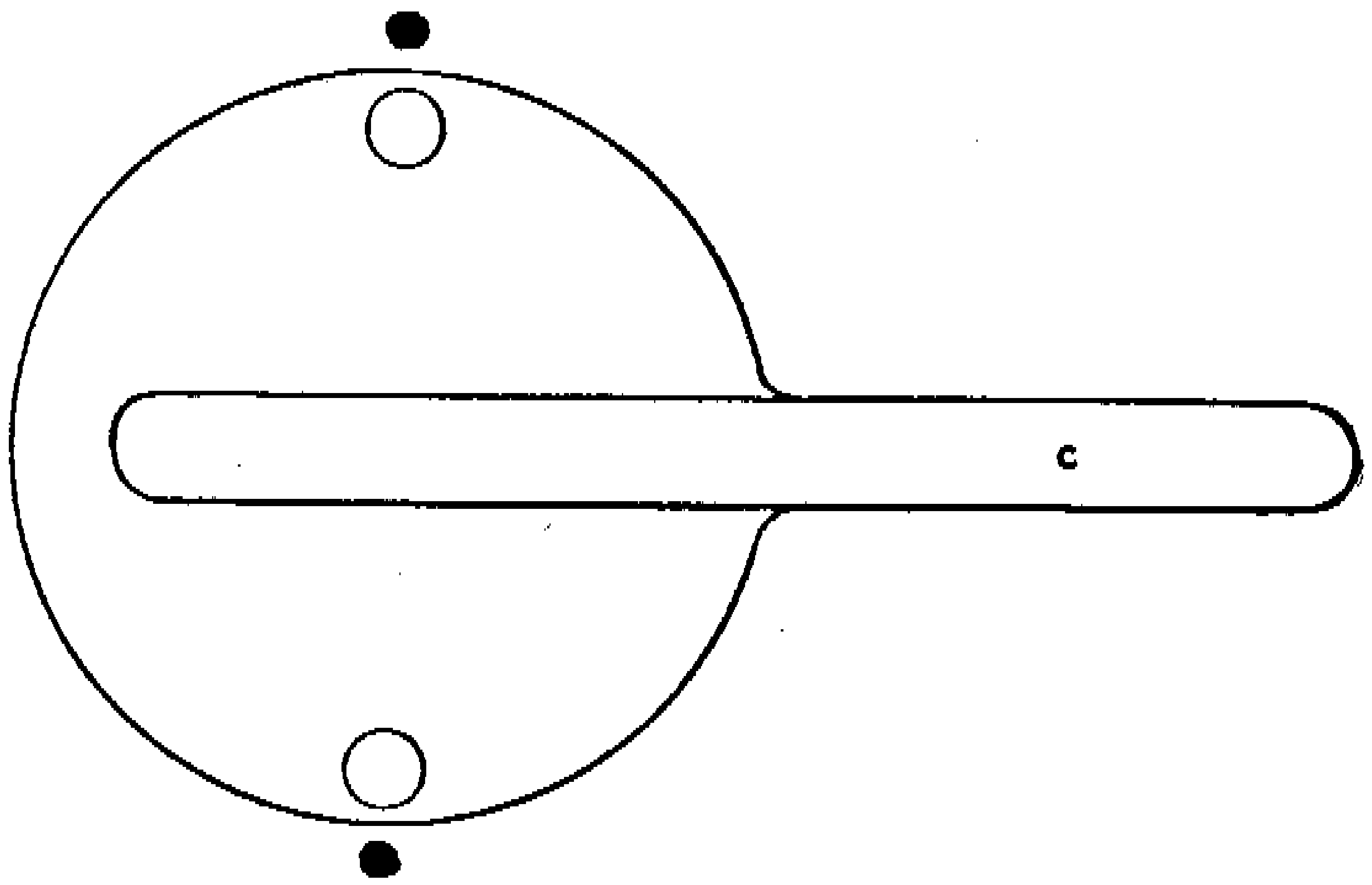
Fig. 12.



The radiation produced by the electrodeless ring discharge is so intense that it is easy to demonstrate its existence by experiments which are suitable for the lecture-room.

One of these is the following. The vessel containing the gas is shaped as in fig. 12. It is a large spherical bulb with a neck about 4 cm. in diameter at one end. The coil for producing the electrodeless discharge is placed round the neck at B, and the bright ring discharge occurs here. Adjoining the ring there is bright luminosity: if the gas is hydrogen, this is a light pink in the layers adjacent to the ring and shows both the Balmer and the second spectrum of hydrogen; this is succeeded by a brilliant red layer showing only the Balmer lines, the boundaries of this layer are fairly well defined. In oxygen the luminosity in the region adjacent to the ring is a brilliant blue. This very bright luminosity only extends a few centimetres from the ring; it is succeeded by fainter luminosity not of the same colour, which can be traced as a luminous cone extending right through the bulb. The glass of the bulb phosphoresces over the area covered by the cone; this phosphorescence is not of the same colour as that due to cathode rays: another proof that it is not produced by these rays is that the distribution of the phosphorescence is not affected when a magnet is brought near it. The existence of this phosphorescence can be shown by the experiment, fig. 13, where C is a glass tube covered with willemite placed along a diameter of the large bulb in which the ring discharge is produced in a plane at right angles to the tube; when the ring discharge passes

Fig. 13.

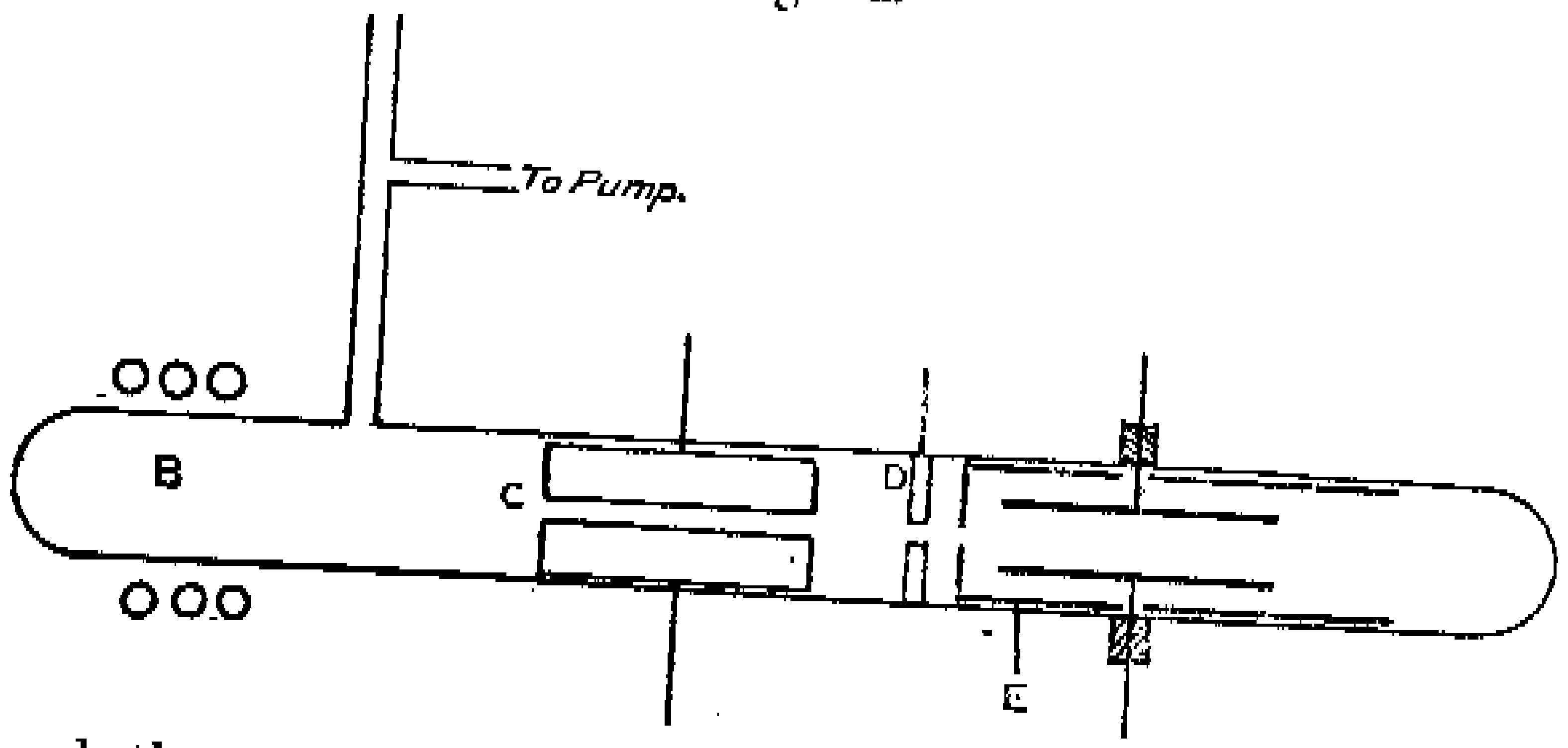


the tube phosphoresces and the distribution of the phosphorescence is not affected by a magnet.

The ionization produced by the radiation can be shown by the experiment represented in fig. 14.

The ring discharge is produced at B. C is the electrostatic filter, consisting of two halves of a brass cylindrical rod, insulated from each other and connected to the terminals of a battery of a large number of small storage cells. D is a brass plug fitting closely into the glass tube, a slit is cut at the centre of this plug so as to be parallel to the space between the two halves of the electrostatic filter. This plug is kept permanently connected with the earth, its object is to shield off any effects due to the high potential of the filter; beyond the plug are two parallel brass plates, so far apart that no radiation passing through the plug can strike against them; one of these plates is connected with the earth, the other to the gold leaves of an electroscope. When the ring discharge is passing at B, the electroscope leaks whether the charge in it is positive or negative, showing that the gas between the plates has been made conductive by the radiation.

Fig. 14.



Summary.

The paper contains an account of experiments on the character of the radiation produced when electric currents pass through gas at a low pressure. The method adopted was to let the radiation fall on a disk of metal and measure the variation in the rate of emission of electrons due to the photoelectric effect when the emission was retarded by an electric field tending to stop the escape of electrons. The theory of the variation of the rate of emission with the strength of the field is worked out, and methods are given for determining from the graph representing the relation between rate of emission and the potential difference in the retarding field the spectrum of the radiation.

The radiation produced by the passage of cathode and positive rays through the gas, that from the negative and anode glows in hydrogen, oxygen, helium, and argon at different pressures are discussed. It is found that the frequencies of by far the greater part of the radiation are comparable with those corresponding to quanta of the order of the ionizing and resonance potentials of the gas, in the case of the radiation due to the cathode rays these radiations are mixed with others of a higher frequency.

In a few cases the radiation was found to be fairly homogeneous, but in general it is a mixture of radiation having a frequency comparable with that of the ionizing radiation with other radiation of a lower frequency.

The electrodeless ring discharge is found to be a very copious and convenient source of radiation of this type, and various lecture-room experiments are described for demonstrating the existence and properties of the radiation.

I have much pleasure in thanking Mr. E. Everett and Mr. Morley for their assistance in making these experiments.

LX. *Electric Double Refraction in Colloids.*

By Yngve Björnståhl [*].

(From the Laboratory of Physical Chemistry, Upsala.)

[Plate XIII.]

By accidental double refraction is meant the phenomenon that a medium, during the action of external agents, assumes optical properties similar to those of a uniaxial crystal. Thus the behaviour is not characteristic for the substance *per se* in its non-excited state, but is produced, for example, by a magnetic or an electric field.

The magnetic double refraction in liquids was first studied by A. Cotton and H. Mouton [†]. In a previous communication the author has given an account of the magnetic double refraction in certain colloids [‡]. Analogous to the phenomenon in a magnetic field a double refraction also appears in an electric field. This action has been subjected to detailed investigations and is often called the electric Kerr effect,

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[*] Communicated by the Author.
[†] *C. R.* cxlv. p. 229 (1907).
[‡] Phil. Mag. xlii. p. 352 (1921).