"THE MECHANISM OF RADIATION AND IONIZATION IN DISCHARGES WITH SPECIAL REFERENCE TO THE HIGH-FREQUENCY GLOW."

A THESIS

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C O N T E N T S.

PREFACE.

The present thesis is a connected record of a series of researches carried out by the writer during the years 1928 to 1932. The work has continuity in the sense that each problem which is considered has its origin in a previous investigation; the thesis is incomplete in the sense that many problems of first importance in connection with the work remain to be solved. As will be appreciated by the reader, the author has been content to follow where his experiments have led him, in every case selecting from the wealth of phenomena at his disposal those which interested him most, or which appeared to have the greatest theoretical importance. At no point has he attempted to lead the experiments in any particular direction. In his humble opinion this ought to constitute the fundamental distinction between University and commercial research.

All the work which is described either has been or is about to be published. At the end of the thesis the previously published papers of which the thesis is a digest are included. These are in order of publication:-

1. "The Ionization of Hydrogen by Its Own Radiations", Philosophical Magazine, 1929.
2. "Arc and Spark Radiation from Hydrogen in the Extreme Ultra-Violet", Philosophical Magazine, 1929.
3. "On the Mechanism of the Electrodeless Discharge", Philosophical Magazine, 1930.
4. "The Ionizing Efficiency of Electronic Impacts in Air",

Proceedings of the Royal Society of Edinburgh, 1931.

5. "Arc, Spark and Glow: a Note on Nomenclature",
Philosophical Magazine, 1932.

6. "A New Thermionic Voltmeter",
Journal of Scientific Instruments, 1932.

There are also included as additional evidence the writer's first two publications which formed the subject of his thesis for the degree of Doctor of Philosophy. These are:-

a). "The Influence of Charged Metallic Points on the Spark Discharge", Philosophical Magazine, 1928.

b). "On the Ultra-Violet Radiations Emitted by Point Discharges", Philosophical Magazine, 1928.

Part of the work described in the sixth chapter with additions will be communicated in the near future to the Philosophical Magazine.

It gives the author pleasure to acknowledge once again his indebtedness to Professor Taylor Jones, whose ever-ready interest and encouragement have contributed much to the success of the investigations. To Professor Crowther his thanks are also due. It was while the writer was Lecturer in Physics at the University of Reading that the work described in Chapter IV was performed. The Research Board of that University supplied a much appreciated grant for the apparatus employed.

INTRODUCTION.

The investigations to be described in this thesis had their origin in experiments performed by the writer in the years 1926-27-28 and described by him in two communications to the Philosophical Magazine, entitled, "The Influence of Charged Metallic Points on the Spark Discharge"[1], and "On the Ultra-Violet Radiations Emitted by Point Discharges"[2]. These preliminary experiments formed the subject of the writer's thesis for the degree of Doctor of Philosophy, and as the genesis of the work to be described in the present thesis, their principal results will be set forth in this introduction.

The Influence of Charged Metallic Points on the Spark Discharge:- It is well-known that a sharp metallic point facilitates the passage of a spark across a gap near which it is placed. The explanation of this effect remained, however, obscure, until in 1925, Wynn-Williams[3] and in 1926, Morgan[4] made careful studies of the associated phenomena. In 1926 the present writer began a series of experiments the object of which was the further elucidation of the effect, and the results of his investigation were summarized as follows:-

"1.

i. That electromagnetic radiations emanate from the air in the immediate neighbourhood of charged metallic points from which electric discharges are taking place in air at atmospheric pressure. The intensity of the radiations increases with the intensity of the discharge.

ii. That the radiations produce photo-electric effects and ionization

iii. That the radiations producing the photo-electric effects emanate only from the neighbourhood of positively charged points.

iv. That the ionizing radiations emanate from the neighbourhood of both positively and negatively charged points.

v. That the photo-electric radiations can penetrate 15 cm. of air at atmospheric pressure.

vi. That the ionizing radiations are absorbed by 3 cm. of air at atmospheric pressure.

2. These results differ from those of Wynn-Williams in regard to the precise locality of the source of the radiations, and in regard to their penetrating powers.

3. A theory is suggested of the action of a charged metallic point in facilitating the passage of a spark between spherical electrodes.

4. This theory differs from that offered by Wynn-Williams in ascribing the greater part of the action to the photo-electric effect.

5. The action of the ionizing radiations in facilitating the passage of the spark is found to depend on the nature and state of the surface of the cathode.

6. The ionizing radiations are found to be capable of facilitating the action of the spark, even when no straight line can be drawn in air from the metallic point to the line of the spark discharge.

7. It is suggested that the action of the ionizing radiations

in such cases is an indirect effect due to the impact of positive ions on the metal of the cathode.

8. The experimental results of Morgan are examined and confirmed, but a somewhat different explanation of them is given.

9. The results of the present experiments are considered in relation to the theory of the spark discharge recently put forward by J. Taylor, and are found generally to support this hypothesis.

10. Some of Townsend's conclusions with reference to his theory of the spark discharge are considered in the light of the present experiments, and modifications of these conclusions are suggested."

<u>The Ultra-Violet Radiations Emitted by Point Discharges</u>:-

It appeared to the writer that the ultra-violet radiations from the point discharge, the existence of which was demonstrated by the previous investigation, were worthy of further study for reasons which were set forth in the introductory paragraph to the second communication to the Philosophical Magazine. That paragraph was as follows:- "In recent papers[(3),(4),(1)] it has been shown that ionizing radiations similar to those discovered by Wiedemann are emitted by the gas in the vicinity of metallic points charged to a high potential. That such radiations (or radiations of slightly longer wave-length) may be of first importance in determining the mechanism of the spark discharge has been suggested by J. Taylor[(5)], and the present writer has described results which appear to support his theory. The experiments described in the present communication were undertaken with a view to obtaining further evidence regarding the nature of these radiations and their relation to the discharge. The experiments are of a preliminary nature, since, so far as the writer is aware, no attempt has so far been made to investigate any part of this region of the spectrum at pressures comparable with atmospheric*. The results obtained, however, fully justify further study of the phenomena exhibited."

The results of this second investigation may be summarized as follows:-

1. It was found to be impossible to experiment with discharges in closed vessels containing air or oxygen, owing to a remarkable spontaneous ionization effect, probably due to the gradual dissociation of the ozone molecules formed in the discharge.
2. Curves were drawn exhibiting the variation with gas pressure of the ionizing and photo-electric radiations from hydrogen and nitrogen, when the gases were excited by a discharge.
3. The variation of the intensity of these radiations when the pressure was kept constant and the discharge current varied was also shown.
4. Tentative explanations of the phenomena exhibited were given.

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* This is not quite accurate. Miss E. Laird in America has recently investigated the Entladungstrahlen emitted by condensed discharges. The statement is true in so far as Miss Laird's technique and approach are quite different.

5. It was suggested that hydrogen was ionized by its own radiations, and this remarkable phenomenon was discussed. It appeared to the writer that the most important result of these experiments was the fact that they suggested the ionization of hydrogen by its own radiations, and when the investigation was described to Section A of the British Association at Glasgow in 1928, Professor H. S. Allen of St. Andrews immediately pointed out that the experiments were not conclusive in that respect. The writer therefore turned his whole attention to designing one or more experiments which would settle the question definitely, and it is from this point that the present thesis begins.

References.

(1). J. Thomson, Phil. Mag., v. p.513 (1928).

(2). J. Thomson, Phil. Mag., vi. p.526 (1928).

(3). C. E. Wynn-Williams, Phil. Mag., i. p.353 (1926).

(4). J. D. Morgan, Phil. Mag., iv. p.91 (1927).

(5). J. Taylor, "Dissertation", Utrecht (1927);
Proc. Roy. Soc. A, cxvii. p.508 (1928).

CHAPTER I.

THE IONIZATION OF HYDROGEN BY ITS OWN RADIATIONS.

The investigation to be described in this chapter consists of two quite distinct parts. In the first part the sole aim of the experiments was to determine if pure dry hydrogen gas may be ionized by the radiations emitted by a point discharge in the same gas: in the second part the attempt was made to demonstrate that the radiations from the discharge which produce such ionization are themselves due to the hydrogen atom or molecule.

Part I.

Experimental Methods.

It may be well to indicate briefly the theory of the previous experiments referred to in the Introduction. The radiations under consideration are of such a nature that the only solid substance through which they are transmitted with sufficient intensity to be detected is a celluloid film less than one tenthousandth of a centimetre thick, and consequently they were produced and detected in the same tube. The point discharge took place in the region P of the discharge-tube. The radiations emitted were detected by their ionization and photo-electric effects in the region Q. Between P and Q an arrangement of shields was placed to ensure that no ions could travel from the discharge to the ionization chamber. Examples of such tubes for producing and detecting the radiations are given in

Figs. 1 and 2 of this chapter and in Fig. 1 of a previous paper [1].

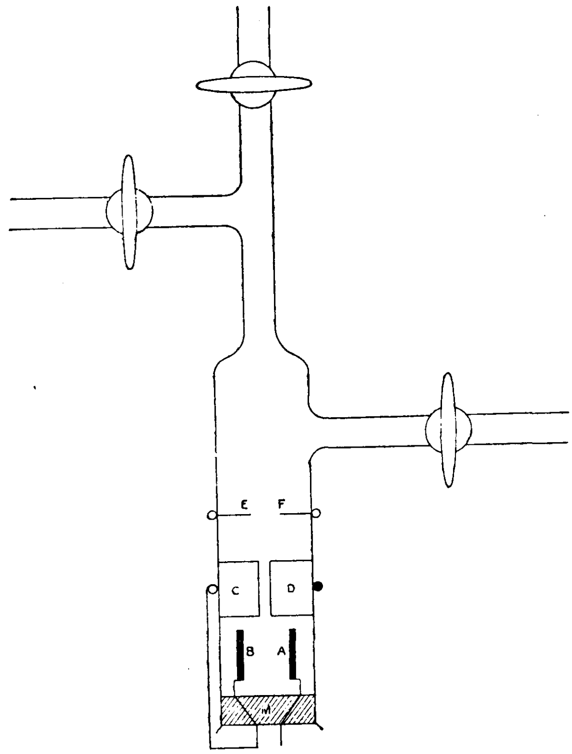
The first series of experiments was made using discharge-tubes which had not been "baked out". The aim of these experiments was to trace any changes which might occur in the ionization current at Q due to the radiations emitted at P, as the gas, walls, and electrodes became gradually free from water-vapour and gases other than hydrogen. In order to obtain the necessary insulation in such a tube, filled initially with moist gas, it was necessary to use a wax sealing round the electrode which measured the ionization current. Consequently such a tube could not be "baked out" at any stage in the investigation.

The second series of experiments was therefore performed with a different set of tubes. These were of the "all glass and metal-seal-in" type, so that they could be "baked out" at a high temperature. By this means the attempt was made to measure the ionization current at Q when the tube and electrodes had been thoroughly dried and "outgassed", the hydrogen which was admitted being pure and dry.

Lastly, it must be mentioned that all these experiments were performed at approximately atmospheric pressure, thus removing many of the dangers of impurity which arise when the pressure is low.

Unbaked Tubes and Electrodes:- The first set of experiments was made with the discharge-tube represented diagrammatically in Fig. 1. A glass cylinder 2 cm. in diameter was connected to three side-tubes. These led to the pump, the mercury pressure-gauge, and the gas system. E and F were the points of two

Fig. 1.



platinum electrodes, half a centimetre apart, and between them the discharge passed. Throughout all the experiments the discharge current was maintained at 1 milliampere. C and D were two brass half-cylinders arranged to prevent the passage of ions from the discharge to the ionization chamber. The slot between them was 2 mm. wide and the cylinders were 2 cm. long. The ionization chamber contained the two rectangular electrodes A and B, the former being connected to one pair of quadrants of a Dolezalek electrometer. These electrodes were so arranged that no radiation from EF fell directly upon them. That they would collect scattered radiations cannot be doubted.

The tube was sealed at M with a mixture of bees-wax and resin. While experiments were being performed, C and B were at a potential of −380 volts with respect to A which was initially at earth potential. The potential of D was +300 volts relative to earth. The lead from A to the electrometer was carefully shielded.

The gas was obtained by the electrolysis of barium hydroxide in a specially constructed Hoffmann's apparatus. The anode was placed half-way up one of the arms at a distance of 30 cm. from the bottom. There was therefore no possibility of any diffusion of oxygen into the hydrogen arm. The gas then passed through a liquid air trap and a capillary tube to the discharge apparatus. The pump used was a Cenco Hyvac, since very low pressures were not required.

As already stated, the method of investigation adopted was to attempt to dry the gas and discharge tube progressively by means of the liquid air. Starting with moist gas, readings were taken of the ionization current at A, when the discharge was passing at EF. Then liquid air was placed round the trap, and the dry gas was passed into the tube. Here it no doubt received water-vapour from the walls and electrodes and became relatively moist again. A reading of the ionization current was again taken. This process of admitting dry gas and of measuring the current was continually repeated until, ultimately, the ionization became constant.

The results of this experiment are shown in the table below. The row "No. of Experiment" indicates the order in which the readings were taken: 1 and 2 refer to moist gas; during 3 to 10 the gas was being progressively dried by the method described above.

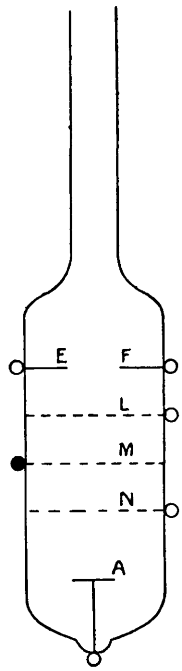
No. of Experiment...	1	2	3	4	5	6	7	8	9	10
Ionization Current..	3	3	4	8	21	30	42	56	56	56

After the ionization current had become constant, a series of readings was taken of the current at different pressures. These readings gave a curve in remarkable agreement with that obtained using moist gas, and obtained under the same conditions (curve (a) of Fig. 2 of a previous paper[1]).

Similar experiments were attempted with different discharge-tubes designed to prevent any radiation from EF impinging upon A or B. The elaborate precautions which were necessary, however, caused A and B to be removed too far from the discharge, and narrowed the beam of radiation greatly. The results with such tubes were never satisfactory on account of this weakening of the intensity of the radiation between A and B. Disturbing effects which were ultimately traced to charge on the walls and the relatively large distance between A and B became prominent. This type of experiment had to be abandoned.

Baked-out Tubes and Electrodes:- The second experiment required a tube of the "all glass and metal-seal-in" type. This is represented in Fig. 2. Every precaution was taken to ensure that no impurities of any description would interfere with the investigation. The gas system was similar to that used previously, except that another liquid-air trap was inserted between the capillary feed and the discharge-tube. No mercury gauge was used,

Fig. 2.



and a single two-way vacuum stop-cock connected the pump, gas system, and discharge-tube. All the connections were glass-sealed.

In the tube itself, L, M, N were discs of wire gauze, and A was a small copper plate. These were heated strongly before they were sealed in, to remove as much occluded gas and vapour as possible. Then the tube was placed in a small electric furnace and baked out at about 350°C. for about 4 hours at a high vacuum. As the tube cooled, it was immersed in a paraffin-wax bath in order that the outer surface of the glass might be coated with a good insulator. Pure dry hydrogen was then admitted to approximately atmospheric pressure.

As in the previous work, the discharge current of 1 milliamp. passed between the points of the platinum electrodes

E and F. The gauze L, which was at a distance of 1 cm. from EF, was connected to earth, while the gauze M, 1 cm. below L was maintained at a potential of +300 volts. The gauze N, 1 cm. from M, was maintained at -370 volts, while the plate A, connected to the electrometer, and initially at earth potential, was 1.4 cm. from N. This arrangement of potentials and distances effectively screened the plate A from any currents due to ions produced above the gauze N. It also prevented the passage of photo-electrons from N to A, since the field between N and M was greater than that between N and A.

Experiments with this apparatus showed that when the discharge was passed across the gap EF, the plate A became charged negatively. This current ceased immediately after the discharge was cut off. It appeared to be a true ionization current due to the gas between N and A. The current remained very constant when the discharge current remained constant. It appeared to be quite independent of the number of times that the discharge had already been passed. Moreover, as in a former experiment described in a previous paper[1], the ionization current increased linearly with the discharge current, as the latter was varied between 0.4 and 1.6 milliamp.

Conclusions.

It appears to the writer that the first series of experiments admits of only one interpretation. The sole effect of placing the liquid-air round the trap was to dry and purify the gas. As the gas, tube, and electrodes became drier, the ionization increased. The ionization, therefore must be due to the gas itself. The explanation of the increase in the current may be interesting, but so far as the present experiments are concerned it is a matter for conjecture. That aspect of the investigation will be considered later when more is known concerning the source of the ionizing radiations, but that the result is not quite anomalous is shown by the work of Chattock and Tyndall[(2)] on the electrical wind in very pure hydrogen. These writers have demonstrated that when the gas is very pure, there is a large apparent increase in the velocity of the negative ions emitted by the point in a point-to-plane discharge. It will be shown immediately that a very close connection exists between this phenomenon and the results of the present investigation.

The second experiment is even more conclusive. The currents measured were very large indeed, and remained constant over a large number of experiments. This suggests that no changes were taking place in the gas-content of the tube, an effect which had caused considerable difficulty during earlier observations. It may be concluded then that the ionization observed in this type of experiment, due to radiations from the point discharge, is ionization of the hydrogen gas in the tube, and not of water-vapour or other impurity.

Note on the Investigation by Chattock and Tyndall of the Pressure of the Electrical Wind.

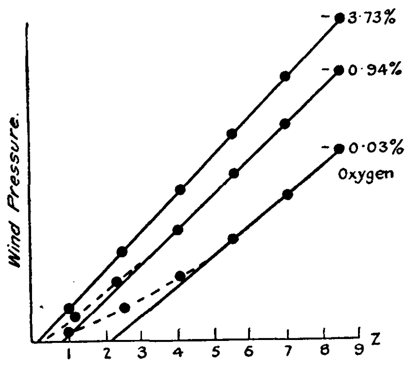
The writer's attention was called to this investigation by Professor Tyndall at the Glasgow meeting of the British Association

The primary object of the experiments was to determine the velocity (V) of gas ions in a field of 1 volt/cm. "Earlier measurements by the wind-pressure method[3] led to values of V which are in satisfactory agreement with those obtained by other methods," but in the particular case of hydrogen the velocity of the negative ions varied very considerably with the purity of the gas.

It may be well to sketch briefly the theory of the experiment. A controlled current of a few microamperes flowed from a sharp platinum point A to a circular perforated plate B, the point and plate being enclosed in an air-tight tube. By means of the sensitive manometer invented by one of the authors for this purpose, it was possible to measure the pressure of the electrical wind at the plate B. A could be moved so that the distance AB (z) could be varied. The experiment consisted in measuring the pressure of the wind (p) for different values of $\underline{z}$, and by this means obtaining $\frac{dp}{dz}$. This allowed the specific velocity of the ions to be calculated.

The curves shown in Fig. 3 (curves II in the communication of Chattock and Tyndall) were obtained by plotting $\underline{p}$ against $\underline{z}$, each curve corresponding to a different percentage of oxygen impurity in the gas. In each case, when $\underline{z}$ is large $\frac{dp}{dz}$ is constant, and this is the result predicted by the authors' theory. It will be noted, however, that as the hydrogen becomes purer, $\frac{dp}{dz}$ decreases, while $\underline{z_0}$, the intercept on the z-axis made by the straight part of the curve produced, increases. Chattock and Tyndall explain the decrease in $\frac{dp}{dz}$ as the gas becomes purer by the hypothesis that there is back-discharge from the plate to the point, and this discharge increases as the percentage of oxygen impurity decreases. How the back-discharge is produced they do not suggest.

Fig. 3.



Two possible explanations are given by the authors of the increase in z_o which accompanies the decrease in oxygen impurity, viz.:-

(i) "The ions from the point may travel an appreciable distance before growing large enough to produce much wind."

(ii) "The gas may be ionized for an appreciable distance from the point - this being equivalent to a lengthening of the point so far as wind production is concerned."

Both of these phenomena are supposed to be enhanced as the gas becomes purer.

The purpose of the present note is to suggest an explanation of the manner in which the back-discharge in these experiments arises, and of the reason why it increases as the gas becomes purer. The same explanation accounts for the existence of $\underline{z}_0$, and for its increase as the oxygen impurity diminishes.

It has been shown by Wynn-Williams [4] and the writer [5] that a metallic point such as that used by Chattock and Tyndall gives rise to ionizing radiations. These have been shown to emanate, not from the point itself, but from the gas in its immediate vicinity, and in the case of an air discharge from gas within 2 to 3 mm. from the point. In air such radiations can produce ionization up to a distance of about 3 cm. from their source; beyond this they cannot be detected. It has also been shown by the writer that the intensity of the radiations is a linear function of the current flowing in the discharge.

This, then, appears to afford the explanation of the back-discharge postulated by Chattock and Tyndall. Considering first the case of impure hydrogen, $\underline{z}_0$ is of the order of 4 mm. and the back-discharge is small. Even in this case, however, the writers found that $\frac{dp}{dz}$ increased as the current in the discharge decreased. This certainly indicates the existence of back-discharge. Moreover, it may be correlated with the fact mentioned above that the intensity of the ionizing radiations increases linearly with the discharge current.

The authors explain the normal $\underline{z}_0$ (4 mm.) by means of Franck's hypothesis that the ions do not reach their full size while travelling a distance comparable with 4 mm. They find it difficult, however, to explain by this supposition the increase in $\underline{z}_0$ as the gas becomes purer. A satisfactory explanation may be given in terms of the ionizing radiations, In order that radiation may occur, recombination or at least inelastic impact of ions with molecules must take place. Hence, within a distance of 3 mm. from the point, many of the ions will lose their charge or their velocity. But the radiations emitted in this region may cause ionization, and in a short distance the excess of negative ions will be re-established. This accounts for the existence of $\underline{z}_o$, and an examination of the results given in the introduction and taken from a previous paper will show that the theory can be applied to both positive and negative discharges in air or hydrogen.

The most interesting phenomenon, however, from the point of view of the investigation which has just been described, is the decrease in $\frac{dp}{dz}$ and the increase in $\underline{z}_o$ as the hydrogen becomes purer. It has been shown earlier in the chapter that the ionization in hydrogen, due to radiations emitted by a point discharge in the same gas, increases enormously as the gas is purified. In the experiments then under consideration the principal impurity was water vapour, but it must be remembered that the passage of the discharge would decompose part of the water and cause oxygen impurity. It is indeed remarkable that this result should agree so well with the experiments of Chattock and Tyndall. The increase in back-discharge as the gas becomes purer, the increase in $\underline{z}_o$ from 4 mm. to 3 cm., are exactly what is to be expected if the radiations become more intense and the gas itself a more perfect absorber. There appears to be no doubt that radiation is more easily excited in the pure gas, since the authors observed that "in the purest hydrogen and for a negative point the whole plate glows brightly over the surface presented to the point". At the end of their communication they remark: "The four phenomena of glow, fall of wind-pressure, shift of negative curve (increase of $\underline{z}_0$), and abnormally rapid combination, all take place within about the same narrow limits of oxygen percentage; it is therefore at least tempting to think that they may all ultimately prove traceable to a single source." It appears to the writer that this source is to be found in the variations in the intensity of the radiations emitted by the gas in the vicinity of the point during the discharge.*

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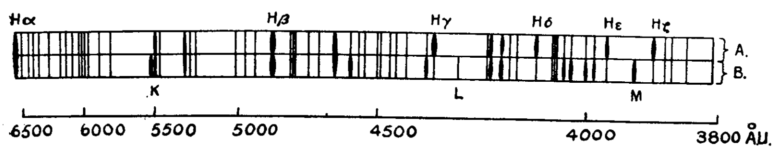
* This discussion of the work of Chattock and Tyndall was first published by the writer in the Philosophical Magazine in June, 1929. At that time Professor J. J. Nolan and J. G. O'Keefe were carrying out an extensive research into the nature of the ions produced by various types of discharges. In a paper appearing in the Proceedings of the Royal Irish Academy in December, 1929 and entitled "The Ions Produced by Discharges at Liquid Surfaces", these authors accept the theory advanced above by the writer, and remark that their observations indicate that ionizing radiations are also emitted by a discharge from a liquid point.

Part II.

The investigations described in Part I show clearly that the radiations from a point discharge in hydrogen gas are capable of ionizing the hydrogen. In earlier experiments[5] it was found that the corresponding radiations from an air discharge were emitted by the gas in the vicinity of the points, and this is the result which is quoted on p,16 as applying to hydrogen. It may be objected, however, that the hydrogen discharge is different in nature from the air discharge, and that it is therefore unsound to deduce that what holds for air will hold for hydrogen. In any event, it was thought advisable to make some further investigations to try to demonstrate that the radiations are not emitted by the metal of the electrodes or by impurities present.

Experiment 1:- The discharge tube shown in Fig. 2 was again employed, filled to atmospheric pressure with pure dry hydrogen. Spectrograms of the discharge were then taken, and these were compared with similar spectrograms of a new hydrogen vacuum tube. In each case the two spectra were taken on the same plate and alongside one another; a copy of a typical photograph is shown diagrammatically in Fig. 4.

Fig. 4.



Spectrum A was taken from the vacuum tube; B from the point discharge at atmospheric pressure between platinum points with about 2 milliamp. flowing. It will be seen that the two spectra are very similar indeed. Out of the sixty or so clear lines present in both spectrograms only the three marked K, L, M in the spectrum of the point discharge are not definitely attributable to hydrogen, and of these three only one can possibly be due to platinum. It was, of course, verified that all the lines in spectrum A are due to hydrogen. The single platinum line, M (3923 A.), is the raie ultime of that element, and is visible when excited platinum is present to the extent of one part in 10^{10}. Consequently, no great significance can be attached to its appearance in this case. In fact, the evidence of the spectrograms is all in favour of the view that the discharge radiations are due almost entirely to the gas.

In passing, an interesting feature of the spectrum of the point discharge may be noted. The spectrum of the vacuum tube consists essentially of the atomic spectrum - the Balmer series. The molecular spectrum in this case is decidedly "secondary". In the discharge at atmospheric pressure the relative intensities of the two spectra are entirely changed. The molecular lines are more intense, while it is difficult to distinguish any of the atomic lines beyond H_γ.

Experiment 2:- To obtain, if possible, more direct evidence with regard to the source of the radiations, another experiment was performed.

A discharge tube similar to that shown in Fig. 2

was fitted with two pairs of similar points, one pair being of platinum, the other of tin, and the distance between the first pair was made equal to the distance between the second pair. Then the intensity of the ionizing radiations from a discharge between the platinum points carrying 1 milliamp. was compared with the intensity of the radiations from a discharge between the tin points carrying 1 milliamp., the detector of the radiations (the ionization chamber AN of Fig. 2) being at the same distance from the source in both cases. The intensities were found to be equal within the limits of experimental error, about 1% of the value of either intensity as measured indirectly by an electrometer Now, if the source of any considerable part of the radiations was the metal of one of the electrodes, one would expect that the greater fusibility of the tin, combined with the general dissimilarity of the metals, would cause some distinct difference in the two intensities. That the result of the experiment was negative at least suggests that the radiations emanated from the gas.

Indirect evidence with regard to the source of the radiations is obtained from a study of the nature of the point discharge itself. In all the experiments so far described the latter was excited by an induction coil capable of giving a 10-inch spark, used in conjunction with a motor mercury-jet interrupter. The current flowing between the points (as measured by a Gaiffe milliamperemeter) never exceeded 2 milliamp., and care was taken to see that the inverse current from the coil was as small as possible by using the smallest possible potential across the primary coil. The only capacity across the discharge was the small self-capacity of the secondary coil. Under these circum-stances, and particularly where the electrodes are of platinum, it has been shown by many spectroscopists that the spectrum of the discharge is due almost entirely to the gas between the electrodes. The discharge consists of what is usually called an "uncondensed spark" followed by a series of "pulsating arcs", but the nomenclature of the subject is so ambiguous that the writer has published a note[6] calling attention to the fact and suggesting a rationalisation. In the next chapter the mechanism of the discharges commonly called "arc", "spark" and "glow" is discussed, and it is shown that the "uncondensed" induction coil "spark" is almost entirely a glow discharge. Hence, it is also consistent with what is known of the fundamental processes of radiation in discharges to attribute the rays now under consideration to the gas itself.

Impulse Radiation.

A most tempting hypothesis to account for the origin of the ionizing radiations is to suppose that they are due to the impact of electrons on the surface of the anode - the impact energy of the electrons being transformed wholly or in part into electromagnetic radiation. This process is analogous to the emission of the X-ray impulse spectrum, and the writer has therefore named the hypothetical radiation similarly.

This theory which would account very beautifully for the apparent high frequency of the rays is unfortunately untenable. The writer's experiments on the exact geometrical source of the ionizing radiations [5] demonstrated quite conclusively that the latter emanated from the air in the vicinity of the anode. Hence impulse radiations cannot contribute to the phenomena. It has been shown by J. J. Thomson [10] and A. Dauvillier [11] that discharges at low pressures are the source of two types of ionizing radiations: (a) very absorbable Schumann radiation, and (b) penetrating X-rays. The latter (impulse radiation) cannot be emitted at atmospheric pressure, or the writer's experiments would certainly have brought it to light.

Conclusions.

The result of the investigation described is (in a word) to show that hydrogen may be ionized by its own radiations. This conclusion is consistent with all the experiments performed, and of no other explanation can the same be said. Nevertheless, F. L. Mohler [12] was unable to detect any photo-ionization of hydrogen from its own radiations and there is no reason to doubt the validity of his experiments. In fact it is now tolerably well decided theoretically that the ionization potential of the hydrogen molecule

$$\text{i.e.} \qquad H_2 + H_2 = H_2^+ + H_2^-$$

is higher than the ionizing potential of the hydrogen atom, and this denies the possibility of direct ionization of the gas by its own radiations. The explanation of the apparent contradiction is as follows:-

From the present experiments no conclusion can be drawn with regard to ionizing potentials. If it could be assumed that the gas in the ionization chamber was normal hydrogen at the time when ionization was taking place, and that the latter took place in one stage, then the result would contradict the accepted theoretical conclusion; but neither assumption is justifiable. The high pressure in the chamber favoured inter--changes of energy between excited molecules, and this in spite of the very short "life" of the latter. Hence it is very probable that the ionization was brought about by multi-stage excitation, due to the molecules absorbing two or more quanta of energy, either from the radiations themselves or by collision with other excited molecules.

It is now known that such multi-stage excitation is fairly common in certain types of experiment. Examples which may be quoted are (a) the low-potential vacuum arc, and (b) the classical experiment of Fuchtbauer on the resonance of mercury vapour. In the former a discharge is maintained with a potential between the electrodes equal only to the first resonance potential of the gas. In the latter mercury vapour was made to emit its complete arc spectrum by absorption of one resonance line and others of lower frequency.

This explanation of the ionization agrees very well with the observed fact that decrease in the gas impurity caused a large increase in the ionization. Obviously for maximum ionization it is necessary that the radiation should be scattered throughout the gas with as little degeneration into energy of lower frequency as possible. This is what would occur in very pure hydrogen, where no other atoms were present to introduce other absorption processes. The explanation, as has been remarked before, also agrees remarkably well with the observations of Chattock and Tyndall.

CHAPTER II.

THE CLASSIFICATION OF ELECTRIC DISCHARGES.

Introductory.

Although this chapter is chronologically the last of the thesis, it is placed at this point in order that the investigations of chapters I and III may be better understood. For the moment the ultraviolet radiations from hydrogen are forsaken to discuss in detail the mechanism of typical discharges at atmospheric pressure.

The purpose of the present chapter is two-fold. First, it is proposed to call attention to ambiguities of terminology which exist with regard to the discharge. Three classes of investigators - the electrical engineers, those engaged in research on the mechanism of the gaseous discharge, and the spectroscopists - employ the terms "arc" and "spark" to define certain phenomena. Unfortunately, the connotation of each term varies considerably from one class to another, so that auxiliary definition is always required, but too seldom given. By physicists in general the terms are used in the sense which was originally intended by the electrical engineers, but, as the progress of research has shown that the phenomena described by them are complex, the words have become not only ambiguous but definitely misleading. The attempt will therefore be made to indicate clearly what each of the three classes mentioned intends to be understood when the term "arc" or "spark" is employed. Secondly, it is proposed to describe a simple experiment which exhibits at atmospheric pressure all the types of electric discharge. From a consideration of the conditions under which each type appears it should be possible to suggest some more exact definitions which will rationalize the nomenclature and destroy the confusion which at present exists.

Electrical Engineering Nomenclature.

In the 'Dictionary of Applied Physics' an electric "spark" is defined as "the sudden discharge of electricity across an air-gap accompanied by the production of light and heat," and the "arc" as "a stream of hot gases carrying an electric current across a gap between two electrodes." Surely these two definitions are not mutually exclusive; it is easy to imagine a spark (so defined) taking the form of an arc (so defined). Yet in practice a distinction between the two is implied. This may be well exemplified with reference to the phenomena exhibited by an induction coil or high-tension magneto.

I. Induction Coil Discharges without a Secondary Condenser.- Suppose the secondary terminals of a coil to be connected to an air-gap with no condenser in parallel, and the primary current to be arranged so that a bright discharge across the gap takes place. Then the evidence of the rotating mirror[7] is that at each break in the primary circuit there is a series of secondary discharges. The first of these is bright, particularly at the outset, and the others are faint. The current is pulsating but unidirectional. A simultaneous oscillograph record of the potential across the secondary coil is of the form shown in Fig. 5[8], where the ordinate measures the square of the secondary potential and the abscissa the time.

The potential peak A gives rise to the first bright discharge, while B, C, D, E are the cause of the fainter, more diffuse ones. In accordance with the customary terminology of electrical engineering, discharge A is called a "spark" and B, C, D, E are called "arcs". The number of arcs which follow the spark depends, of course, upon experimental conditions; it is even possible, by using larger primary currents and small gaps, to obtain a decaying aperiodic arc instead of the pulsations of Fig. 5.

It is difficult to say exactly what is the distinguishing characteristic of the spark in this discharge. Certainly A is considerably brighter than B, C, D, E. In fact, the aggregate intensity of the last four is usually small compared with the intensity of the spark. There is also evidence that the initial part of discharge A is of a different nature from the rest - it is the earlier stage which is most brilliant. But neither of these qualities is of much use in forming a definition. Perhaps the best properties of the spark which can be used to distinguish it from the arc are the potential difference required for its production and the time which it takes to occur. A is associated with a very large potential difference between the electrodes - something of the order of 20,000 volts/cm. in air at atmospheric pressure, while in B, C, D, E the corresponding inter-electrode potential difference is less than one-tenth of this. Also, the initial spark is of very

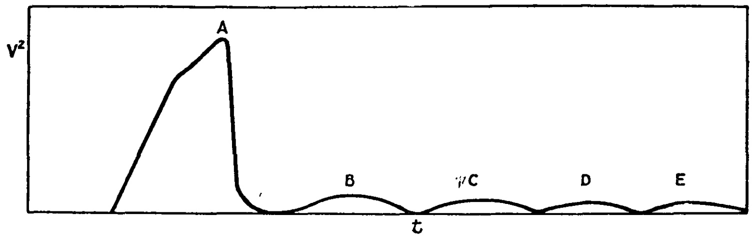


Fig. 5.

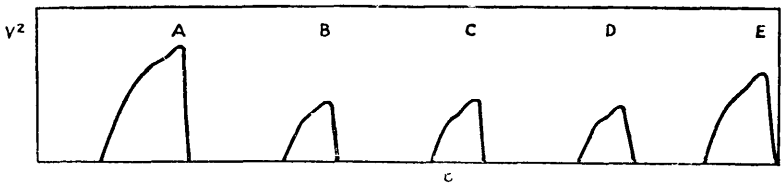


Fig. 6.

short duration. It is a sudden rush of electricity accompanied, as is seen from Fig. 5, by a very rapid decrease of potential.

II. Induction Coil Discharge with a Secondary Condenser.

Suppose, now, a condenser to be placed in parallel with the air-gap, and the primary current again arranged so that bright discharges are obtained. In this case one break of the primary circuit gives rise to a series of discharges of a different type. These, when examined by means of the rotating mirror, prove to be slightly brighter than the others. An oscillograph record of the secondary potential is of the general appearance of Fig. 6.

In this case each discharge A, B, C, D, E is called a spark, and each presents the general appearance of A of the discharge without a condenser. Often each discharge of this type contains more than one spark - there may be as many as six associated with one potential peak. If the primary current is greatly increased, a time comes when the régime of Fig. 5 begins in a modified way. The pulsating arc makes its appearance, and the number of sparks is reduced to one or two, corresponding to one or two distinct potential peaks. Again, it is evident that the most constant property of the spark is the high associated potential. All the peaks A, B, C, D, E are of the order 20,000 volts/cm., although in general they are not so large as A of Fig. 5. Hence it seems that the common usage of electrical engineering terminology is simply to associate the name "spark" with a bright high-potential discharge.

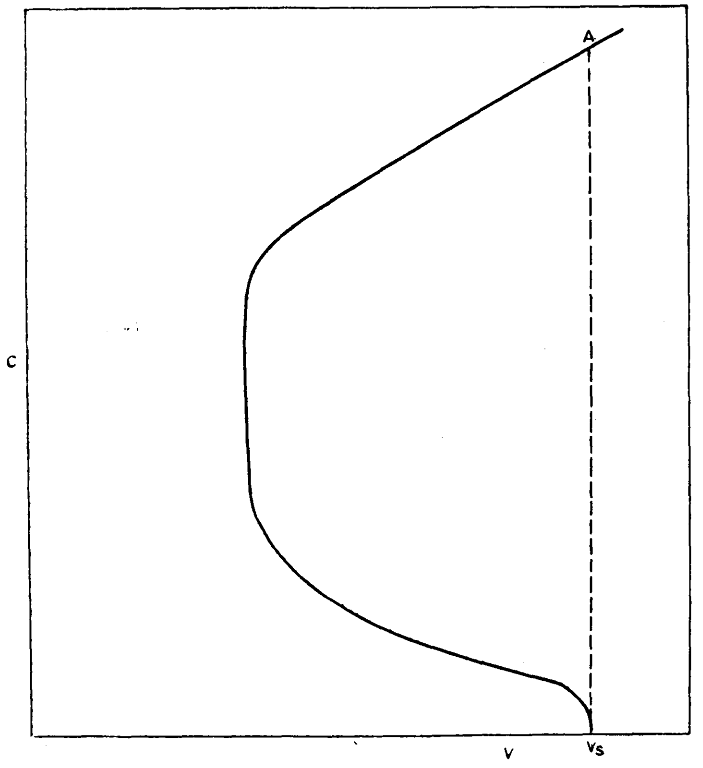
Nomenclature employed in connection with the Gaseous Discharge.

The mechanism of what has been called by modern physicists the "spark discharge" has been the subject of innumerable investigations. In this connection the word "spark" is seldom used as a substantive, the "sparking potential" being the important concept. If, however, the spark is to be defined at all, then it must be as the initial stage of any discharge of electricity through a gas, where the current is carried entirely by gaseous ions between cold electrodes. The "sparking potential" is the minimum steady potential which, when applied for an indefinite time between the electrodes, produces an appreciable current through the gas; it is a function of the nature and pressure of the gas, the shape of the electrodes and their distance apart, and, probably, the photoelectric emissivity of the electrode surfaces.

These definitions imply a considerable knowledge of the nature of the discharge, and the wording of the definition of the spark is particularly significant. It is now well known that the general shape of the current-potential characteristic of a gas discharge between cold electrodes is as shown in Fig. 7, where the abscissa measures the potential difference between the electrodes, and the ordinate the current flowing in the discharge. Such characteristics have been carefully studied by Taylor, Penning, and Clarkson[9].

It follows from the nature of this curve that although the potential difference must be raised to V_s (Fig. 7) to start the discharge, the latter may be maintained at a much

Fig. 7.



smaller voltage. Hence, if the current in any experiment is not controlled by resistance in the circuit, immediately after the discharge commences the conditions correspond to point A on the characteristic. This is the reason for defining the spark as the <u>initial stage</u> of the discharge. The curve shown in Fig. 7 is really a corona and glow characteristic; the spark is represented by an infinitesimally small portion of the curve at V_s.

It is rather more difficult to suggest a definition of the "arc" which will be representative of the nomenclature employed in connection with the gaseous discharge. As distinct from the spark, the arc in this connection is to be associated with a hot cathode at which thermionic emission is taking place. In practice, however, unless a heated filament of tungsten or some other metal of high boiling point is intentionally used as the cathode, thermionic emission requires that the latter should be at such a temperature that it will be partly vaporised. Hence, leaving out of account special techniques, an arc is a discharge in which the current is carried by the metal vapour as well as the gas. This definition forms a sufficiently marked contrast to that of the spark.

Comparing these definitions with the loose ideas acquired from a study of the engineer's use of the terms arc and spark, it is immediately obvious that some readjustment of nomenclature is necessary. The rather ghostly spark of the researcher on the mechanism of the discharge is so faint as to be almost invisible, and the maximum current passing during such a régime is of the order of microamperes. The typical engineer's spark results from the discharge of a large condenser. It is of enormous light intensity, and the current in it is of the order of hundreds of amperes.

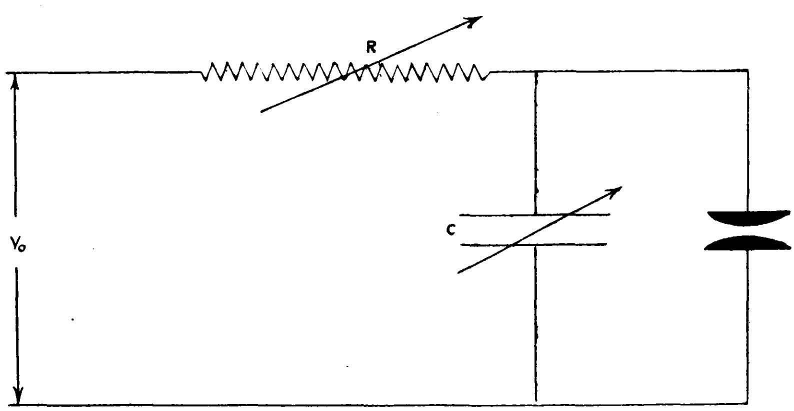
The Nomenclature of Spectroscopy.

Only a word is required in this connection. The "arc" spectrum of an element is that produced when the atom or molecule is returning to its normal state from one of higher energy. It is therefore typical of the un-ionized element, or in the extreme case, of the recombination of an electron with a singly ionized atom or molecule. The "spark" spectrum or enhanced spectrum is that produced by the ionized element returning to its most stable ionized state. In the extreme case it is produced by a multiply ionized atom recombining with an electron. The use of the terms "arc" and "spark" in this manner arose from the empirical study of spectra before the analysis given above was understood. It was found that certain lines in the complete spectrum of an element were not present when the substance was excited by an arc discharge, but were present in the spark. The arcs and sparks which are meant are, of course, those defined by the terminology of the engineers. It is now known that the excitation of the enhanced spectrum depends upon high current density and high electric field strength. These are characteristic of the engineer's spark - hence the connection. Yet the spectra exhibited by a typical spark discharge are indeed varied. Four spectra are obtained with varying degrees of intensity; (a) the arc spectrum of the gas between the electrodes; (b) the spark spectrum of the gas; (c) the arc spectrum of the metal of the electrodes; (d) the spark spectrum of the metal. In no case is the total intensity of the two spark spectra as large as that of the other two. The spark actually enhances the arc spectrum in addition to causing the spark lines to appear. If the spectra of the gas between the electrodes are required, no condenser is used. Under such circumstances, so long as the discharge current is small, only a few faint metal lines appear. If, on the other hand, a condenser is placed across the gap, the spectra of the metal electrodes become brighter and the gaseous spectra are partially masked. The explanation of these spectral phenomena will appear when the details of such discharges are considered later.

Spark, Glow, and Arc at Atmospheric Pressure.

A simple circuit which exhibits all types of discharge at atmospheric pressure is shown in Fig. 8. The variable condenser

Fig. 8.



C, shunted by the spark-gap is connected to a direct-current high-voltage supply through the variable resistance R. In the experiment performed by the writer the spark-gap electrodes were copper spheres 3 cm. in diameter, and the supply voltage was about 1600. R could be varied from 2 to 0.1 megohms, and C in steps from 2 to less than 0.0001 microfarads. A microscope was focussed on the gap. The type of discharge obtained depends on the values of R and C.

I. Capacity Discharges.- With C of the order of a microfarad, and the gap adjusted so that sparks would pass at 1500 volts (gap about 0.05 mm. in length), regular discontinuous discharges were obtained, the time between each depending upon the value of R. With $C=2\mu F$, and $R=2$ megohms, about 13 seconds elapsed between each discharge. The time was reduced to 1 second, when R was equal to 0·2 megohms. In fact, as will be shown below, the time _t_ between two successive discharges is given by the equation $t=ACR$, where A is a constant depending on the length and nature of the air-gap. Each discharge of this type is bright, and, of course, carries a large current. The latter is oscillatory, being due to the discharge of the condenser, and typical in every way of the engineer's spark. It may be noted that the spectrum of the radiation emitted from such slow flashes is a mixture of copper and air lines, but by far the greater part of the light is due to the band spectrum of nitrogen.

If C is gradually decreased the flashes become more and more frequent, until, when $C=0.001\mu F$ and $R=0.2$ megohms, the circuit emits an audible note of frequency about 200/sec. At the same time the spectrum of the radiation emitted undergoes a change. The copper lines become more prominent relative to the air when C is less than $0.001\mu F$, the discharge is distinctly green in colour, indicating the presence of intense copper radiation.

II. The Glow Discharge:- If the condenser capacity is still further reduced, a time comes when the intermittent discharges, each of an oscillatory nature, cease abruptly, and an entirely different régime begins. The discharge is now continuous and unidirectional; it is indeed a typical glow. The negative electrode is partly covered by a blue disc - the cathode glow - the area of which appears to vary directly with the current. Immediately beyond this is the Faraday dark space, while beyond that again is the red positive column, occasionally faintly striated and ending in a bright anodic spot. These details can, of course, only be seen under the microscope; if higher potentials are used in the hope that the glow may be lengthened, convection currents of air in the gap bend the positive column so far upwards that the glow is extinguished. By making the axis of the gap vertical, the glow may be lengthened to about half a centimetre, but this is approximately the limit.

This glow discharge at atmospheric pressure has been noted and partly investigated on numerous occasions, although it does not appear to have been recognised that it is similar to the low pressure phenomenon. It has been observed in researches on the arc[13], but it was discovered and has been further analysed during researches on the mechanism of the gaseous discharge[14]. The writer cannot find that it is in any way different from the typical low pressure glow either with regard to its appearance and spectrum or with regard to the ionization processes involved. The band spectrum of nitrogen is responsible for almost all the light emitted, but, as the current is increased, the green copper lines begin to be prominent. If the resistance R is continuously decreased (C being approximately zero), the glow degenerates into the "true arc", and the copper spectrum completely gains the ascendancy.

Thus by varying C and R, it is possible with the simple apparatus described to demonstrate all the phenomena usually entitled "arc", "spark", and "glow". A consideration of the mechanism of each in this simple case is helpful in formulating exact definitions.

Characteristics of the "Spark".

The discharge which usually goes by this name is obviously to be associated with the discharge of a condenser. All sparks, in other words, are capacity effects. Sparks may be obtained at any gas pressure, and indeed all the effects mentioned above as taking place in air at atmospheric pressure were obtained at pressures as low as a tenth of a millimetre of mercury. It is, however, more difficult to obtain regular sparking of a small condenser at low pressures. This is to be attributed to the greater mobility of the ions. Even in the case of an "uncondensed" discharge of an induction coil, the capacity of the secondary coil is sufficient to produce the first spark. Indeed, if the resistance in the experiment just described was made sufficiently high, the capacity of the gap itself was sufficient to prohibit the formation of the unidirectional glow. There can be no hesitancy, therefore, about associating the discharge commonly called a spark with the discharge of a capacity. Yet, even if the discussion given has succeeded in properly classifying this discharge, it has not made the common nomenclature more palatable. The condenser discharge is a mixed one; it contains at least two ionizing factors, which can hardly be associated in a fundamental definition. As has been observed, rapidly recurring "sparks" cause a large rise in temperature of the electrodes, so that metal vapour is liberated, and thermionic emission takes place. This introduces an arc element into the discharge. Although this is not present to the same extent in slow flashes, or where the capacity is small and there is a high resistance in the charging circuit, the tendency exists, and in condensed induction coil discharges the metal vapour plays an important part. The writer is therefore of the opinion that the terms to denote typical discharges should be redefined in terms of the knowledge we now possess of the processes at work.

Suggestions as to Rationalisation.

It is suggested that the nomenclature of the investigators of the gaseous discharge should be universally adopted. The following definitions would result:-

Spark:- The initial unstable stage in any discharge between cold electrodes.

The spark thus defined is associated with the sparking potential which may be measured, but the spark itself is a condition rather than an observable phenomenon.

Arc:- A discharge in which the current is wholly or partially carried by the metal of the electrodes.

This is an observable state. Any ordinary discharge at atmospheric pressure would fall into this category. The definition takes no account of special techniques for the production of gaseous arcs by means of externally stimulated thermionic emission.

<u>Glow</u>:- A discharge between cold electrodes, when the current is entirely carried by gaseous ions.

Again this is an observable state so long as the energy available at the gap is controlled by circuital resistance.

To exemplify the connections between these discharges consider the following hypothetical experiment. A direct-current potential difference is applied across an air gap in parallel with which there is no capacity, and in series with which there is no resistance. What will occur?

As soon as the potential difference is equal to the "static sparking potential" for the given gap, a small capacity discharge will take place. This in its initial stage is a spark, but, owing to the shape of the corona and glow characteristic (Fig. 7), it becomes a glow almost immediately. Simultaneously the capacity oscillations die out. The glow is then carrying a current of a few milliamperes. If the electrodes are of such a nature that a high temperature develops at the points where the discharge is occurring (low heat conductivity), and if the boiling point of the cathode is lower than the temperature reached (which will usually be the case), some of the metal is vapourized. This increases the current, since the ionizing potential of the metal is lower than that of the gas. Hence a still higher temperature is developed. The process is cumulative, and in a very short time the discharge takes the form of an arc. Since this amounts to short-circuiting the gap, the current is only limited by the power available.

In general, electric discharges are mixed, containing both of the components, arc and glow. Of this nature is the induction coil discharge, whether condensed or uncondensed. A consideration of the power available in each case explains the types of spectra which are obtained.

The Frequency of the Capacity Discharges of the Circuit shown in Fig. 8.

Suppose that the sparking-potential of the gap is V_s, and the potential at which the discharge ceases is V_M. It may be assumed as a good approximation that V_M is independent of the capacity of the condenser, although this is not so obvious as might at first sight appear. Let t represent time and i the current through the resistance R. Then, if, when $t = 0$, $V = 0$,

since
$$\frac{V_0 - V}{R} = i = C\frac{dV}{dt}$$

and therefore
$$C\frac{dV}{dt} + \frac{1}{R}V - \frac{V_0}{R} = 0$$

we have
$$V = V_0\left(1 - e^{-\frac{t}{CR}}\right)$$

The potential V becomes V_s after a time T, given by

$$T_1 = CR \log \frac{V_0}{V_0 - V_s} \quad \ldots \ldots \quad (1)$$

Subsequently the potential never falls below V_M. If, when $V = V_M$, $t = 0$, the discharge having ceased, then

$$V = V_0 - (V_0 - V_M)\, e^{-\frac{t}{CR}}$$

and the potential becomes V_s again after a time T_2, where

$$T_2 = CR \log \frac{V_0 - V_M}{V_0 - V_s} \quad \cdots\cdots \quad (2)$$

Hence if it may be assumed that the discharge takes place in a negligibly small time, the time between each is given by T_2, or, the frequency of "sparking" by

$$n = \frac{1}{CR \log \frac{V_0 - V_M}{V_0 - V_s}}$$

<u>The Mean Potential of the Condenser</u>:- Assuming, as before, that the discharge takes place in a negligibly small time, the condenser potential varies between V_M and V_s, rising to V_s and dropping suddenly to V_M. The mean potential, therefore, is

$$V_A = \frac{1}{T_2}\int_0^{T_2} V\,dt$$

$$= \frac{1}{T_2}\int_0^{T_2}\left\{V_0 - (V_0 - V_M)e^{-\frac{t}{CR}}\right\}dt$$

$$= \frac{1}{CR \log \frac{V_0 - V_M}{V_0 - V_s}} \int_0^{CR \log \frac{V_0 - V_M}{V_0 - V_s}} \left\{V_0 - (V_0 - V_M)e^{-\frac{t}{CR}}\right\}dt$$

$$= V_0 - \frac{CR\,(V_s - V_M)}{T_2}$$

But
$$V_s = V_0 - (V_0 - V_M)e^{-\frac{T_2}{CR}}$$

$$\therefore \quad V_A = \left\{V_0 - \frac{CR(V_0 - V_M)(1 - e^{-\frac{T_2}{CR}})}{T_2}\right\}$$

This result will be used later to calculate V_M.

$$V_M = V_0 - \frac{T_2(V_0 - V_A)}{(1 - e^{-\frac{T_2}{CR}})CR} \quad \cdots\cdots \quad (3)$$

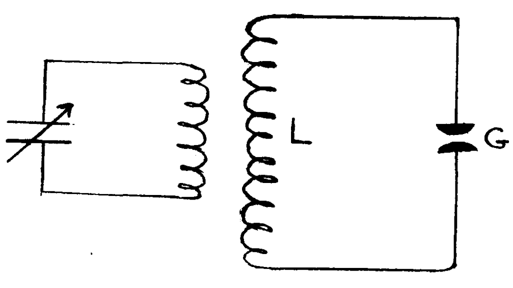
Further Investigations of the Condenser Discharge.

To complete the analysis of the various discharges which has been given, a more detailed examination of the processes at work in the "spark" was necessary. The experiments which are about to be described had as their aim the determination of the exact mechanism of the condenser discharge. They show how far the current in the latter is carried by gaseous ions, and how far the current is due to thermionic emission. They also explain successfully the well-known action of a condenser shunted across a switch in arresting the arc which occurs when the switch is opened; and conversely, they explain why the "pulsating arc" in an induction coil discharge is suppressed by the insertion of a capacity in parallel with the spark-gap.

(a). High Frequency Discharges:- Since the discharge of a condenser is a high-frequency phenomenon, it was thought advisable to examine the discharges obtained by means of sinusoidal alternating potentials of frequency 10^6 to 10^7 per second.

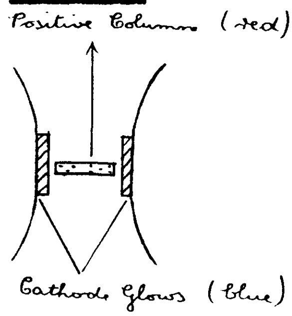
I. Discharge at a Gap in Parallel with a Large Inductance:- The circuit is shown in Fig. 9.

Fig. 9.



The large inductance L in parallel with the self-capacity of the gap G was loosely coupled to the oscillating circuit of a valve oscillator. The frequency of the latter circuit was tuned to resonance with the spark-gap circuit. When the gap G was small enough, discharges took place. These were silent glows which, examined through the microscope, were found to be exactly similar to the D.C. glow already described, except that each electrode was covered with a blue cathode glow. The appearance of the discharge is shown diagrammatically in Fig. 10.

Fig. 10.



At a frequency of $1{\cdot}11.10^{6}$/sec., it required a peak potential difference* of 3,500 volts to start a 1 mm. discharge. This could be maintained at 1,200 volts. A 5 mm. glow could be maintained at 2,200 volts. The "sparking-potential" for the 1 mm. gap was roughly equal to the sparking potential for the same gap using direct current.

II. Discharge at a Gap in Parallel with Another Capacity:- The circuit of Fig. 11 was now fitted up.

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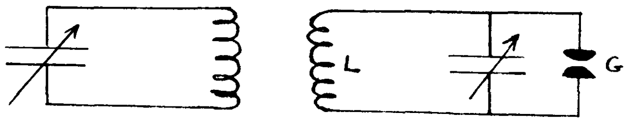
* Measured by the methods described in Chapter VI.

Fig. 11.



The circuits were tuned to resonance. Again 1 or 2 mm. discharges could be obtained at G, but with this arrangement these were "sparks" - bright noisy discharges, intermittent in character and quite unlike the previously described glow. The introduction of the capacity across the gap prohibited the formation of the glow. The capacity discharges showed metallic lines in their spectrum.

Conclusions:- These two experiments teach us (i) that the spark, although a high-frequency phenomenon, is not a high-frequency glow, (ii) that "sparks" can be obtained from condensers even when these are charged by an alternating potential difference of frequency 10^7.

(b). The Resistance of the Gap in a Condenser Discharge:-

The circuit of Fig. 8 was again fitted up with a view to determining at what potential the condenser discharge goes out; or in other words, to determine the value of V_m in equations (2) and (3).

First, the attempt was made to measure V_s and T_2 in equation (2), and hence to deduce V_m, but it was found to be almost impossible to measure V_s accurately. Therefore equation (3) was used, where V_s is eliminated, and the new potential V_A, the average voltage across the capacity, is introduced. It was found to be possible to measure V_A to within 5%, and T_2 with about the same degree of accuracy. Hence V_M was calculated.

The result was instructive. For every case examined V_M was less than 50 volts, and on the average was less than 20 volts. Hence when a condenser discharges through an air gap practically its whole energy is dissipated, and the discharge can be maintained with less than 100 volts across the gap. These condenser discharges were then obtained with gaps of the order of 1 cm., and in every case the result was the same.

This shows that the resistance of an air gap to a condenser discharge is very small, a result which is confirmed by observations on the damping coefficient of the high-frequency condenser oscillations, and this in turn appears to be conclusive evidence that the condenser discharge is not an air discharge at all, since, with a gap 1 cm. long at atmospheric pressure, the resistance to a current of gaseous ions is of the order of 50,000 ohms.

The conclusion, therefore, is that the "spark", during a considerable part of its life at least, is an "arc" discharge, the current being carried by thermions and metallic ions.

(c). <u>The Temperature of the Electrodes in a Condenser Discharge</u>:- To test the point the following interesting experiment was performed. Spherical copper electrodes were covered with platinum foil about 0·1 mm. thick. The platinum was beaten to fit the spherical surfaces and soldered to the copper. These electrodes were used in the circuit of Fig. 8. The glow discharge was easily obtained with C = 0, and after 10 minutes running with a current of 12 milliamps. flowing the platinum surfaces were examined. Neither anode nor cathode showed the slightest sign of tarnishing in spite of the fact that the cathode was very hot.

A 1μF condenser was then placed across the gap, and a single "spark" was passed between the platinum electrodes. The latter were then examined. It was found that both surfaces were punctured where the "spark" had passed. The surrounding metal was slightly discoloured.

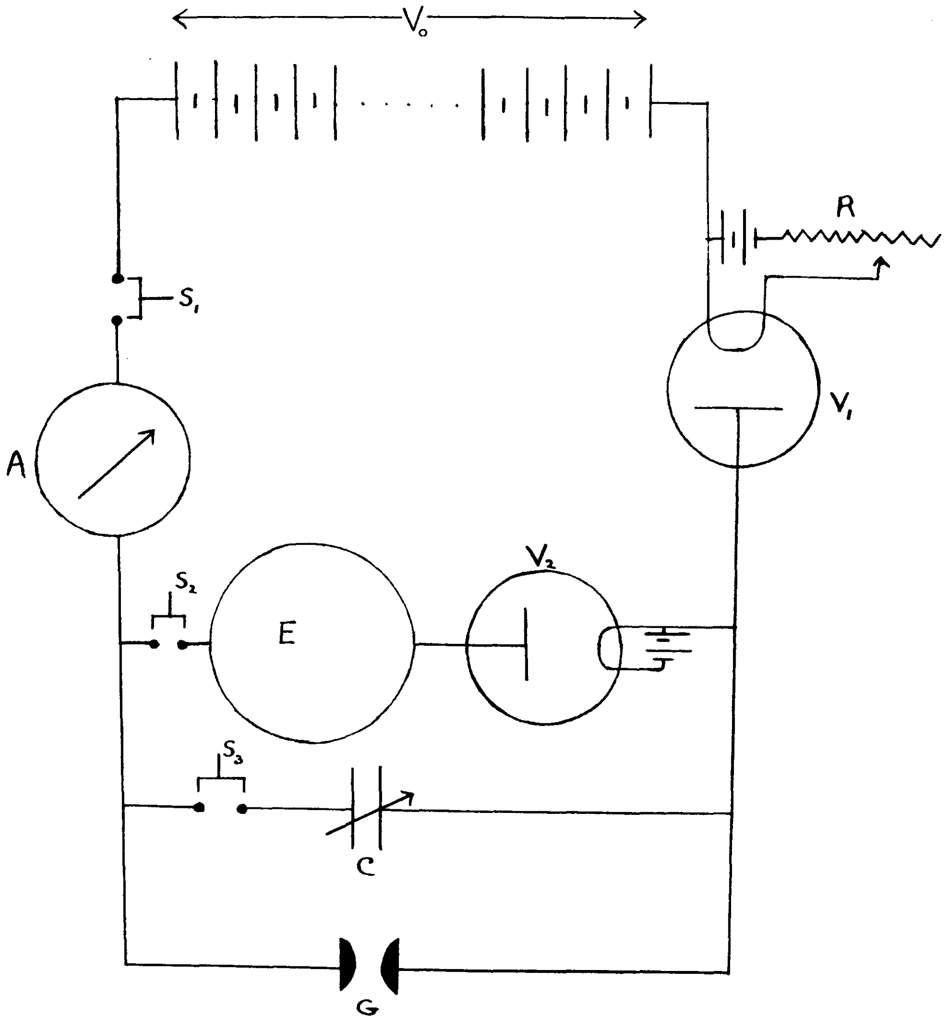
The inevitable conclusion, that a temperature of about 2,000°C. was reached at each electrode during the passage of the discharge, strongly supports the view that thermionic emission and metallic vapour conduction play a large part in carrying the current in the "spark".

(d). The Action of a Condenser in Suppressing an Arc:-

A useful circuit for the investigation of the subject is that used by the writer and shown in Fig. 12.

In the writer's experiments a bank of dry batteries gave a potential difference $V_0 = 1820$ volts. V_1 was a large rectifying valve capable of passing a current of 0·5 amp. at 10,000 volts. By means of the resistance R, the current flowing to the gap could be controlled. The valve V_2 in series with the electrostatic voltmeter E, reduced the effective capacity in parallel with the gap G without

Fig. 12.



affecting the readings of the instrument. The capacity C and gap G were as before. S_1, S_2, S_3 were switches, and A a milliamperemeter.

By adjusting the resistance R it was possible to obtain a current of 15 milliamps. in the circuit AGV, with the gap closed. If S_3 was out, so that there was no capacity across the gap, a glow appeared when the gap was opened. The glow could be made any length up to about 1·5 cm. If now the switch S_3 was closed, and the uncharged condenser brought into the circuit, in every case the glow at G was suppressed. If the gap was small, intermittent condenser discharges took its place: if the gap was large, the glow simply disappeared.

The explanation of this phenomenon is perfectly simple. The current going to charge a condenser of capacity C from a battery of potential V through a resistance R is

$$i = \frac{V}{R} e^{-\frac{t}{CR}}$$

If now any resistance is placed in parallel with this condenser, the current flowing in that resistance will be negligible compared with the current i at $t = 0$, and if, as is generally the case, only a limited power is available, this means that practically no current flows through the parallel resistance at $t = 0$. If we think of a parallel resistance with self-capacity there will actually be an inverse current to the condenser at $t = 0$. Hence in the experiment described, when the switch S was closed, the potential across the gap fell almost instantaneously to zero, and the glow ceased.

The second experiment is just as instructive. If the glow is taking place in the gap, and the switch S_3 is closed, the condenser C being initially charged to a higher potential than that across G, then a violent capacity discharge takes place, and the glow vanishes. Here the initial glow is supplied with a very large additional amount of energy from the condenser. The result is an arc which short circuits C. Then the potential has to be built up again from the battery, and the discharge goes out.

The second experiment typifies the action of the condenser in condensed induction coil "sparks". The potential-time curves of Fig. 6 owe their peculiar shape to the two actions described

(i) the short-circuiting action of the condenser energy.

(ii) the time required by the condenser to charge up again.

The circuit of Fig. 12 can be made to imitate an induction coil very well by suitably adjusting the capacity C and resistance R. The insertion of the switch S_3 may be made to imitate exactly the insertion of a Leyden jar in the induction coil circuit.

The work described in this chapter may be compared with the beautiful investigations of J. W. Beams[(15)] and of E. O. Lawrence and F. G. Dunnington[(16)]. Making use of the well-known action of the Kerr cell, these authors have been able to photograph the spectra of the capacity discharge both in its earlier and later stages. Some of the spectra were obtained in the first 4.10^{-8} sec. after the spark commenced. They have also photographed the discharge directly by the same methods. Their results correspond exactly to the analysis which is given in this chapter from a different point of view.

CHAPTER III.

ARC AND SPARK RADIATION FROM HYDROGEN IN THE EXTREME ULTRA-VIOLET.

Introductory.

Returning now to the study of the radiations from the point discharge, the present chapter contains an account of experiments the aim of which was to determine which of the numerous hydrogen spectra was responsible for the ionization observed. Previous investigations[1] had shown that there was much to be learned from a quantitative study of the variation in intensity of the radiations as the current flowing in the discharge was varied. The object of these new experiments was to exhaust the possibilities of such a mode of approach by utilising the refinements of technique suggested by previous work. The accuracy of the measurements involved was made the subject of careful investigation, so that accidental variations in readings (exceedingly common in discharge tube work) might not be considered as real phenomena. It is claimed for the results which are to be given later that all the phenomena observed are characteristic of the gas hydrogen.

Experimental Arrangements.

The Gas System:- The experiments consisted essentially in measuring the ionization current in a region Q of a discharge tube caused by the total radiation emitted by a point discharge in a region P. Maintaining the pressure of the gas at a constant value, this ionization current was measured for different values of the discharge current, the aim of the experiment being to establish the exact relation between the two currents. In a previous investigation it had been found that the value of the ionization current for a given discharge current at a given pressure depended to a very great extent on the purity of the hydrogen. It was therefore necessary to obtain the gas in as pure and dry a state as possible. To this end the hydrogen was generated electrolytically in a specially constructed Hoffmann's apparatus, designed to prevent the passage of oxygen from the anode to the cathode. To reach the discharge tube the gas passed through a capillary tube, two wide tubes containing calcium chloride, a tube containing phosphorus pentoxide, and two liquid-air traps. One of the traps was in the discharge tube system itself (i.e., that part of the system which was sealed off when experiments were in progress), which also contained a simple pressure gauge, and was connected through a vacuum stop-cock to a Hyvac pump. The entire gas system was glass sealed, thus avoiding any foreign vapours from wax or rubber.

Such a system does not, of course, give pure gas when first used. The glass, the powdered phosphorus pentoxide and calcium chloride, and the glass wool which was also included, all contain much occluded gas and vapour: but, if the system is evacuated and filled with hydrogen a large number of times, sufficient time being allowed after each filling to dry the gas thoroughly over the drying agents, then the moisture disappears from the glass, and the occluded gases are displaced by the hydrogen. In the present experiments it was found to be unnecessary to use liquid air. When the gas was allowed to remain over the drying agents for four or five days, it was found to be fairly dry on entering the tube.

The tests of the purity and dryness of the gas were such as had been suggested by previous investigation. These tests depend upon two properties of the impure gas described in the introduction and in Chapter I. If any oxygen is present in the discharge tube, the ionization current caused by the discharge persists for some time after the latter has been cut off. The magnitude of this residual current is a rough measure of the amount of impurity present. This test is a very delicate one, as has been shown repeatedly in the course of this and previous experiments. An even finer test, however, is given by the variation of the ionization current when the pressure and discharge current are kept constant, the same sample of gas being used for a number of readings. When the dry gas is introduced into the tube, the ionization current has a comparatively large value. If, however, the tube itself is not dry, successive readings show a diminution in the ionization, indicating that the tube is giving up its moisture to the gas. This test still gave a positive result after the apparatus had been is use for a month. The diminution in the ionization is a consequence of the fact noted in Chapter I that the drier and purer the gas the more easily it absorbes the radiations. When these tests failed to detect any impurity in the gas, it was assumed that the experiments could be performed with safety.

<u>The Discharge Tube</u>:- This has already been described in

Chapter I and is shown diagrammatically in Fig. 2. During the present experiments L was maintained at a potential of -310 volts, M, which was 1 cm. below L, was connected to earth, while N, 1 cm. below M, was connected to L, being therefore at -310 volts. A was connected, as usual, to the insulated quadrants of a Dolezalek electrometer, and was initially at earth potential.

As before, this arrangement of gauzes effectively screened A from any ions generated in the gap EF. Moreover, owing to the relative distances of N from M and A, it was exceedingly unlikely that any photo-electrons emitted by N could arrive at A. It may therefore be assumed that, whem a discharge was passing from E to F, any current passing from N to A was due to the ionization of the gas in the vicinity of N or A.

The discharge between E and F was produced by means of an induction coil used in conjunction with a motor mercury-jet interrupter. Every precaution was taken to render the action of the coil reliable. The mean current (secondary) was measured by means of an accurate meter, reading to about 600 microamperes. The average current between E and F was about 200 microamperes.

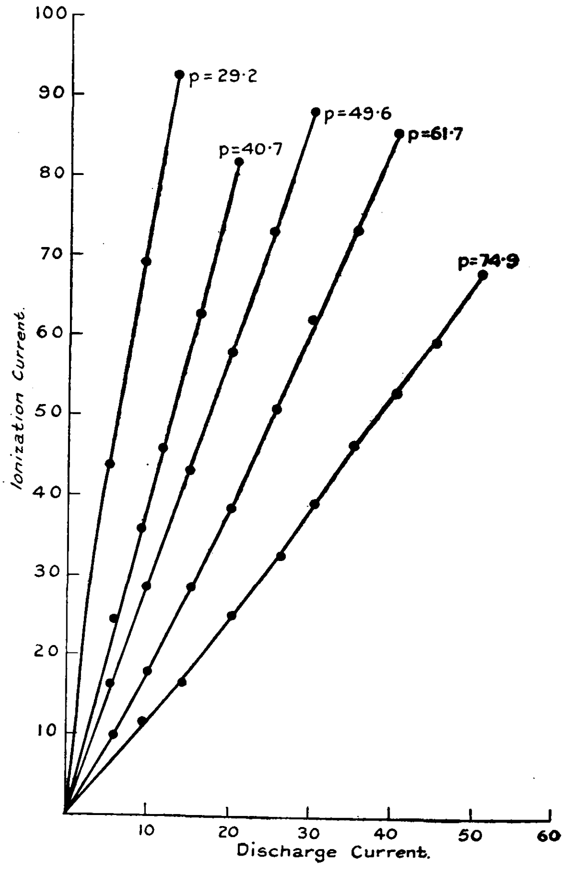
The other measurements necessary were of pressure and ionization current. The former was read from an ordinary barometer tube pressure gauge. This was sufficiently accurate for the purpose. The ionization current was measured by means of a Dolezalek electrometer. Since the currents were very large - of the order of 10^{-12} ampere - a phosphor-bronze suspension was used, the sensitivity of which was 10mm. to the volt with the scale at 1 metre distance. It was necessary that the sensitivity should remain very constant; this was verified on numerous occasions.

Variation of the Ionization Current with the Discharge Current, the Pressure remaining Constant.

Both the gas and the tube being so dry as to give no indication of impurity when the aforementioned tests were carried out, the discharge tube was filled with hydrogen to atmospheric pressure. A small current was then passed through the gas, and it was verified that the ionization current remained constant to 1% of its value over a large number of readings. To avoid any progressive effects of temperature changes, a 10 minutes' pause was allowed after each reading, and the readings were taken in a definite order. Starting with a discharge current of about 50 microamperes, readings were taken at 50, 100, 150, ... 500, 500, ... 150, 100, 50. Usually, owing to temperature variations, and perhaps to a very small unexamined change in the gas, the readings taken with decreasing discharge current were slightly greater (maximum difference, 2%) than those taken with the discharge current increasing. Then the pressure of the gas was reduced to about 60 cm. of mercury, and the same series of readings was taken, In general, as the pressure was reduced, it became necessary to reduce the maximum discharge current, since the ionization became too large for accurate measurement, Thus, at about 30 cm. the maximum discharge current was about 150 microamperes. In Fig. 13

the results of these experiments are shown. The abscissa measures the discharge current; the ordinate the ionization current. The curves are drawn for different pressures in the same sample of gas.

Fig. 13.



Discussion of the Results.

The curves shown in Fig. 13 are typical of all the samples of gas which were used. The absolute value of the ionization current at a given pressure and for a given discharge current varied slightly from sample to sample; but the shapes of the curves did not so vary. It is claimed that they are typical of the gas hydrogen.

Suppose that the source of the radiations is at the point B (the discharge), and that the ionization current which is observed takes place in the region C. Then, so long as the pressure of the gas is not varied, the ionization is a measure of the intensity of the radiations at C. Also, so long as the pressure is not varied, the absorption of the radiations between their source B and the region C remains constant, and hence the ionization current at C is a measure of the intensity of the radiations <u>at their source</u> B. The only assumption made here is that the <u>quality</u> of the radiations does not vary with the discharge current. Hence, if this assumption is justifiable, the shape of any particular curve in Fig.13 exhibits the mode of variation of the intensity of the radiations from the discharge as the current in the latter is varied.

It is evident from a casual examination of the curves that, the pressure remaining constant, the radiation intensity increases in a <u>roughly</u> linear manner with the current. This had already been observed (1). A more careful examination of the curves leads to more definite and more interesting conclusions. The curves, as shown in the figure, have been drawn to pass through the origin, since the radiation intensity must be zero when the discharge current is zero. The curves at 74.9 and 61.7 cm. of mercury have a small but definite concavity upwards; the two curves obtained at 49.6 and 40.7 cm. are almost straight lines; the curve at 29.2 cm. is slightly convex upwards. Also, in three of the four curves taken at high pressures the point representing the radiation intensity at lowest discharge current lies above the curve through the origin. These are all real phenomena of the gas; they are shown in all the curves which have been taken.

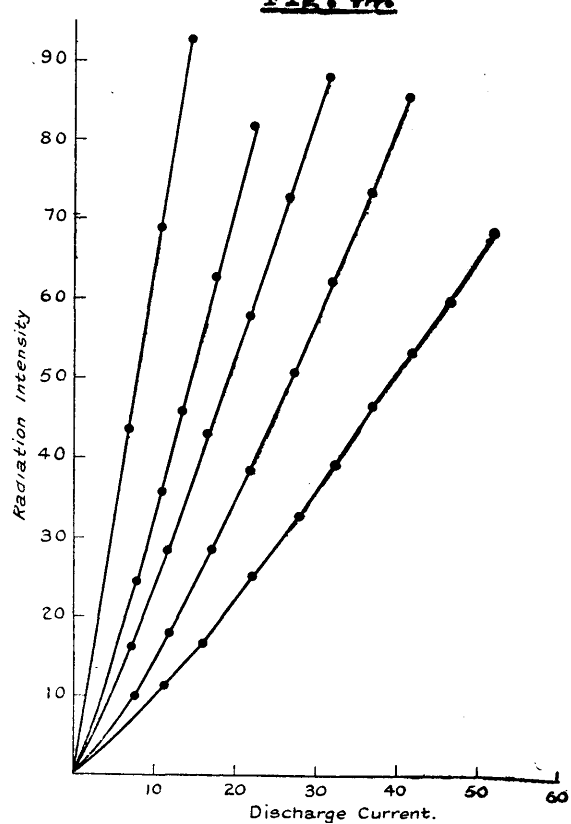
The results can be reduced to order in a very simple manner. If the origin is taken about two discharge current units to the left of the origin shown in Fig.13 , the curves become very much simplified. The anomalous points now lie on the curves; the curves all show a tendency to concavity upwards; and the concavity, or variation from a straight line, decreases uniformly as the pressure of the gas is reduced. Is there, then, any reason for believing that the true origin of coordinates lies a little to the left of the origin given by the amperemeter?

The current measured by the meter should be the mean current through the secondary of the coil. The current in the coil varies in a periodic fashion; if this current is represented by c, the current measured by the meter should be proportional to $i = \frac{1}{T}\int_0^T c\,dt$, and i should be accurately proportional to c. But even under the best conditions there is always a certain amount of "inverse current" in the secondary circuit. This current is sufficient to produce a very small discharge, and its direction is opposite to that of the current at "break". Hence it is to be expected that the current measured by the meter should be less than the true mean current by a small quantity. Under the conditions of the experiment this quantity would seem to have been of the order of two units.

That this inverse current was present was shown by a very interesting experiment. The current flowing in the discharge was reduced by means of a series resistance in the primary circuit. As the current fell to zero, it was observed that the discharge was still just visible in the dark. On increasing the resistance in the primary circuit, the meter actually showed a small negative deflexion due to inverse current. The explanation is to be found in the fact that, while the current at "break" depends upon the current flowing in the primary circuit (which was reduced by adding resistance), the inverse current at "make" depends upon the total E.M.F. across the primary circuit (which was not varied by adding resistance). By using a large series resistance in the primary circuit it is possible to make the inverse current as large as the current at "break".

Fig. 14 shows the corrected curves for the variation

Fig. 14.



of radiation intensity with discharge current. The curves have again been made to pass through the origin. They will now be considered in detail.

All the curves can be represented by the expression

$$I = k_1 i + k_2 i^2 \quad . \; . \; . \; . \; . \; . \; . \quad (1)$$

where I is the radiation intensity (ionization current) and i is the discharge current, k_1 and k_2 being constants. Evaluation of k_1 and k_2 for the curve taken at 74.9 cm. of mercury leads to the expression

$$I = K(200i + i^2),$$

$$\text{or} \quad k_1/k_2 = 200.$$

This value is characteristic of the curves taken about atmospheric pressure. The curves obtained at lower pressures are amenable to the same treatment, but, as the pressure is reduced, k_2 tends to zero - the curves become straight lines.

Theoretical Interpretation of the Results.

The use of the corrected values for the secondary current gives a measure of the total current flowing in the discharge, and it has been found that the radiation intensity is proportional to the sum of two quantities one of which is proportional to the total current and the other to the square of the total current. It might be suggested that the two terms in equation (1) represent a second approximation to a function which could be expressed as an infinite series in powers of i. The writer is not inclined to accept this suggestion.

Radiation from a discharge may arise from two principal causes: it may be emitted by the processes following inelastic impact

(i) between an ion and a neutral molecule, or

(ii) between two ions.

Assuming that the pressure is constant, and that the field of electric force in the gap is not affected to any extent by variations in the discharge current, then the probability of radiation arising from the impact of ions on neutral molecules will be proportional to the number of ions in the gap, that is $I = k_1 i$, where I, k_1, i have the meanings assigned to them above. Making the same assumptions, the probability of radiation arising from the impact of ions with ions will be proportional to the product of the number of ions of either sign in the gap, that is

$I = k_2 i^2$, where k_2 is again a constant.

Radiation following inelastic impact between an ion and a neutral molecule is arc radiation - i.e., radiation from an excited un-ionized atom or molecule, and radiation following inelastic impact between two ions is spark radiation - i.e., radiation from an excited ionized atom or molecule. Hence the general conclusion is reached that in a gas discharge, if the current is varied without seriously varying the potential, the gas pressure being constant,

(a) the arc radiation emitted is directly proportional to the discharge current, and

(b) the spark radiation emitted is proportional to the square of the discharge current.

Hence, if the ionizing radiation is emitted by both processes in the discharge, the intensity will be given by the expression

$$I = k_1 i + k_2 i^2 \quad \ldots\ldots\ldots\ldots (1)$$

which is the expression already found empirically for the experimental curves.

This hypothesis, as it has been stated above, requires considerable justification. An objection to it which immediately suggests itself is that the mechanism of radiation from the discharge is exceedingly complex, and that the simple physical picture given above of each inelastic collision absorbing one electron and giving rise to radiation is obviously in no way real. This objection is not so important as it seems, if attention is concentrated not on the radiation processes, but on the excitation processes which give rise to radiation.

The writer's contention can best be explained as follows:-

Consider the action of one electron or negative ion in its passage through the gas. Its collisions with other molecules or ions may result in the following phenomena.

1). Excitation of a molecule.

2). Excitation of a positive ion.

3). Ionization of a molecule.

4). Ionization of a positive ion.

5). Recombination.

Apart from these actions, the negative ion may be neutralised at an electrode, and may collide ~~in~~elastically with other ions or molecules. Processes (1), (3) and (5) ultimately give rise to arc radiation. In processes (1) and (5) this is obvious. In process (3) other ions are formed the negative parts of which repeat the actions detailed. Ultimately the positive parts, in common with all the other positive ions in the gap, are either neutralised at the cathode or recombine with a negative ion. In either case arc radiation is again emitted. Hence, processes (1), (3) and (5) give arc radiations. Similarly, processes (2) and (4) ultimately cause the emission of spark radiation, the demonstration of this being along exactly similar lines.

Considering now the macroscopic aspect of the problem, it is clear that for a given pressure, current and potential difference across the discharge, a factor could be chosen to represent the average quantity of radiation produced by one ion under these conditions. This factor would be of the form $n_1 + n_2$, where

n_1 = the number of quanta of arc radiation produced, and

n_2 = the number of quanta of spark radiation produced.

Returning to the microscopic study of the discharge, the processes which contribute to n_1 (i.e., (1), (3), (5)) are totally independent (except for (5)) of the number of ions in the gap. Number (5), however, represents an infinitesimally small fraction of the radiation, since it only applies to those ions from which the discharge had its beginning and which were not neutralised at an electrode. Hence n_1 is a constant, and I_1, the intensity of the arc radiation, is a linear function of the discharge current, the gas pressure and voltage remaining constant.

Similarly, the probability of the processes which contribute to n_2 occurring (i.e., (2) and (4)) is a linear function of the number of positive ions in the gap, and that causes I_2, the intensity of the spark radiations, to vary as the square of the discharge current.

If the above hypothesis be assumed, it may be concluded that the experiments show that the greater part of the ionizing radiation emitted by the discharge has its source in the impact of ions with neutral molecules. When the pressure is high, a small proportion of the radiation is due to purely ionic impact; but, as the pressure is diminished, these ionic impacts become of smaller relative importance. When the pressure is less than half an atmosphere, it is estimated that less than one-thousandth of the radiation intensity is due to this source.

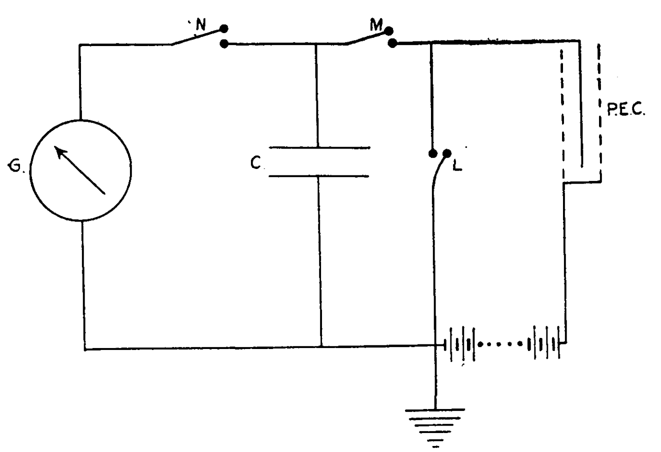
It is a matter of some difficulty to classify in the category of glow or spark a discharge such as that which has just been discussed. The true "glow arc" takes place at a relatively low potential, the true spark at a very much higher potential. The evidence of the rotating mirror has shown that the discharge under consideration is a mixture of both phenomena. A high potential spark is followed by a number of low potential "arcs". This is particularly the case at high pressures, where the conductivity of the gas is least. As the pressure diminishes, the arc begins to predominate, until the discharge degenerates into its typical low-pressure form. Thus the evidence of other investigations confirms the result arrived at in the present paper by means of the new hypothesis, since the arc radiation is chiefly emitted by neutral atoms or molecules, while the spark radiation is typical of the interaction of ions.

Experimental Verification of the New Hypothesis.

The hypothesis put forward in the above analysis appears to be sufficiently important to justify exhaustive tests of its validity being made. The writer has carried out a rough test for a glow discharge.

A neon glow lamp such as is supplied for spectroscopic work was used as the discharge. The current was measured by a milliamperemeter (0 - 5 milliamp.). The detector of the radiation (visible) was a photoelectric cell supplied by the General Electric Co. (Type KMV6 - this is a vacuum cell, the cathode being a monomolecular layer of potassium on copper oxide). The method of measuring the photoelectric current was suggested by Professor Crowther, and is certainly worth description. The circuit is shown diagrammatically in Fig. 15.

Fig. 15.



P.E.C. represents the cell, L,M,N are well-insulated keys, C is a capacity of about $1\mu F.$, and G is a ballistic galvanometer.

When the cell is exposed to light, the cathode is connected to the capacity which is allowed to charge up for a given time. It is then discharged through the galvanometer and the deflexion noted.

The method has many advantages:-

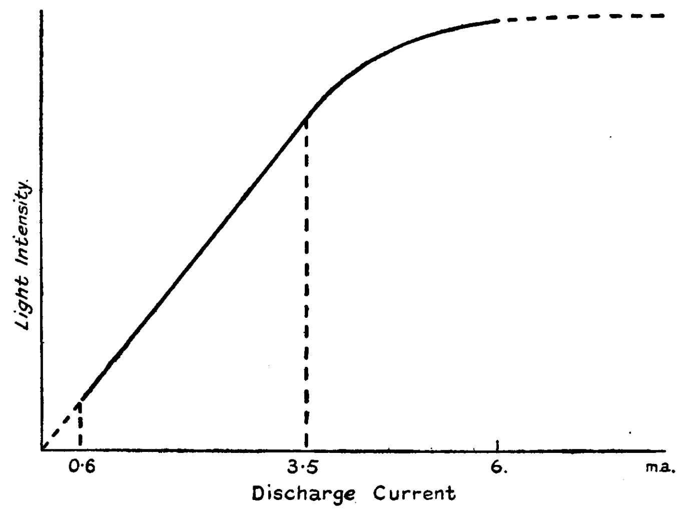
1. The measuring instrument is a robust galvanometer which need not be particularly sensitive.
2. So long as the insulation of the condenser is good, there is no limit to the sensitivity of the method; the galvanometer deflexion varies directly as the time of charge.
3. The potential of the cathode, which is also the potential difference across the condenser, need never rise above 0.1 volt.

In the particular experiment carried out by the writer the photoelectric current was of the order 10^{-8} ampere. The galvanometer sensitivity was about 240 mm. per microcoulomb; the time of charge was 30 sec. and, of course, large deflexions were obtained. This method for the measurement of reasonably large ionization or photoelectric currents is, in the opinion of the writer, superior to any form of electrometer.

The photoelectric cell was first calibrated. It was found that with 120 volts across the cell the current was accurately proportional to the light intensity. Then the neon lamp was set up in the vicinity of the cell and the p.e. current was measured for discharge currents from 0.5 to 6.0 milliamp. The full line in Fig.16 represents a typical result.

The dotted line is the suggested form of the curve outside the limits of observation.

Fig. 16.



It will be seen immediately that the curve is in complete agreement with the writer's hypothesis. Practically all the light from such a neon glow is due to the arc radiation from the gas. The curve of light intensity against discharge current is a straight line from 0 to 3.5 milliamp. A saturation intensity appears to be reached at about 5 milliamp.

When the current is small, the theory given above is completely verified. When the current is such, however, that the number of ions in the gap is of the same order as the number of gas molecules in the gap, the light intensity will begin to depend also upon the number of the latter. Ultimately a stage will be reached where the light intensity will be proportional to the number of neutral molecules, and thus a saturation intensity will appear. The value of the discharge current, i, at which the light intensity becomes saturated will be a function only of the pressure of the gas. If it were possible to try the experiment with the same lamp at different gas pressures, i should be found to vary directly as the pressure of the gas.

The writer did not find it possible to pursue the investigation further, or to try the same experiment with a typical "spark" source, owing to his having promised to take up the research described in the following chapter.If the experiment were performed in the best way, monochromatic light would be used with some form of optical photometer. Should the hypothesis be found to conform to such a test, it might be possible, where the light intensity was sufficiently great, to utilize it to investigate the ultimate source of discharge spectral lines.

CHAPTER IV.

THE IONIZING EFFICIENCY OF ELECTRONIC IMPACTS IN AIR.

Introductory.

In all research on discharges there is one quantity which is of great theoretical importance and which has not received the attention that it deserves, namely, the average energy required by a moving electron to produce one pair of gas ions. The whole mechanism of gaseous conduction is bound up with this simple process of ionization by impact, and the purpose of the present chapter is to describe experiments the object of which is the determination of the total ionization produced in air by an electron moving initially with a specified energy.

Various estimates of this quantity have already been made[17] using widely varying electron velocities and very different types of apparatus, but the agreement between the results obtained is not such as to obviate the necessity for further research. For a given initial electron energy the number of ions produced per electron as determined by Eisl is almost one and a half times the number as determined by Lehmann and Osgood. It was thought, therefore, that a careful investigation was desirable, since it should be possible to determine the quantity concerned with much greater accuracy than is indicated by these results.

The investigation has a fundamental significance. In spite of the large number of researches directed in recent years towards an examination of the properties of the moving electron, there is still no certainty as to the exact mechanism of ionization by impact. The minimum electronic energy necessary for ionization is well known, and the experimental results justify the accepted atomic theory; but the average energy transfer at ionization, when an electron is completely absorbed in a gas, has not received adequate experimental treatment. The present investigation appears to indicate that the energy spent by high-speed electrons in producing one pair of ions in air is 37 ± 2 electron volts. This value is higher than the mean of previous measurements.

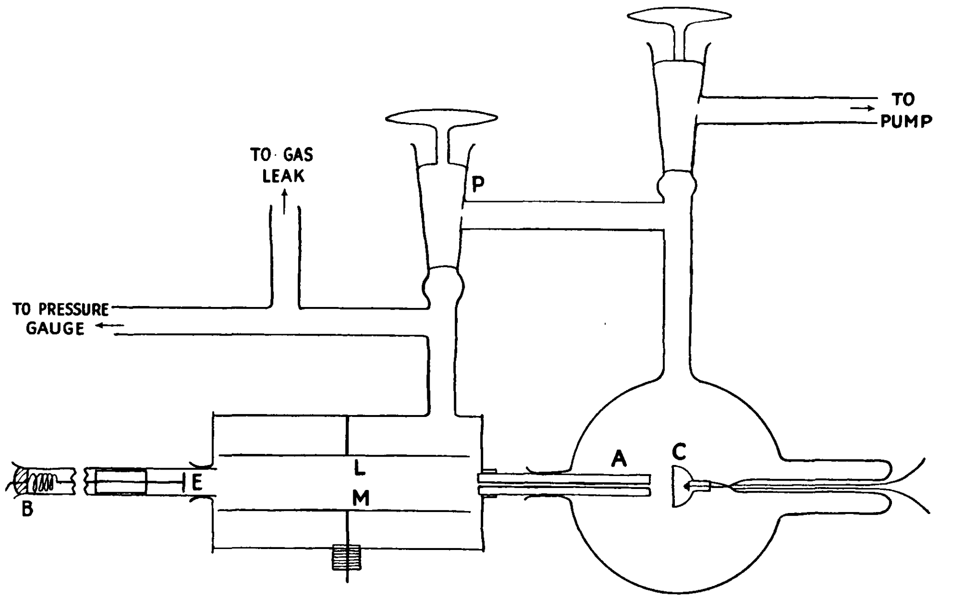
Experimental Arrangements.

1. General Theory of the Method:- It was decided to make the apparatus as simple as possible and to attack the problem in the most direct manner. An approximately homogeneous beam of electrons was shot into an ionization chamber. The electron current I, the average energy of the beam V (in electron volts), and the ionization current C were measured. Hence, the energy V_0 (electron volts) spent in producing one pair of ions was found by means of the formula $V_0 = (I/C)V$.

In order that the equation should hold, it was necessary to ensure (a) that the electrons were totally absorbed in the gas, and (b) that no recombination of the ions produced could take place.

2. <u>The Apparatus:</u>- Fig./7 is a sketch of the apparatus employed. The spherical glass chamber on the right contained the elements for the production of the electron beam. C was a tungsten spiral

Fig. 17.



with a hemispherical focussing cap, forming the cathode. The emitted electrons were accelerated towards the cylindrical metal anode A, which was 14 cm. long and pierced centrally by a 2 mm. diameter capillary tube. Part of the electron beam moved down the capillary tube to the metal ionization chamber on the left of the figure. This was 20 cm. long and about 10 cm. in diameter, and contained the two parallel plate electrodes L and M, arranged to give a very uniform field near the centre of the chamber. L was connected to the ionization chamber, while M was insulated by an ebonite plug. At the end of the chamber away from the capillary tube and exactly opposite the latter, there was inserted a quartz tube about 2 cm. in diameter and 60 cm. long. This contained an aluminium rod at the end of which was a small circular electrode E. The rod was surrounded at one point by a small iron cylinder and was connected through a hard wax plug by a fine wire to the outer atmosphere at B. By means of the iron cylinder and a horse-shoe magnet it was possible to move the electrode E back and forward inside the chamber. It could be brought to within 1 mm. of the end of the capillary tube.

3. The Vacuum System:- The vacuum system was designed to maintain as low a pressure as possible in the chamber where the electrons were being produced, while the ionization chamber was at a very much higher pressure. The metal capillary tube formed the high air resistance, all the other connecting tubes being as wide as possible. Fig.17 is self-explanatory. The two chambers were connected through the vacuum stop-cock P. The production chamber was connected as directly as possible to a two-stage mercury diffusion pump, while on the other side, near the ionization chamber, a gas leak and pressure gauge were incorporated. The manometer was a shortened McLeod gauge, capable of detecting a pressure of 0.0001 mm. The leak consisted of a tube of calcium chloride joined to a long, fine capillary tube which led to a large air reservoir. This reservoir could be pumped out to any desired pressure by means of an auxiliary pump. It contained phosphorus pentoxide and was always connected through a vacuum stop-cock to a tube of soda lime and to the atmosphere. Thus the amount of air leaking into the apparatus could be easily controlled with accuracy, and the air reaching the ionization chamber was reasonably free from water-vapour and carbon dioxide. When the apparatus was in use, a gas pressure

of 0.1 mm. in the ionization chamber did not raise the pressure in the production chamber to 0.001 mm., the tap P being closed and the pumps working. Practically the whole pressure change took place in the capillary tube.

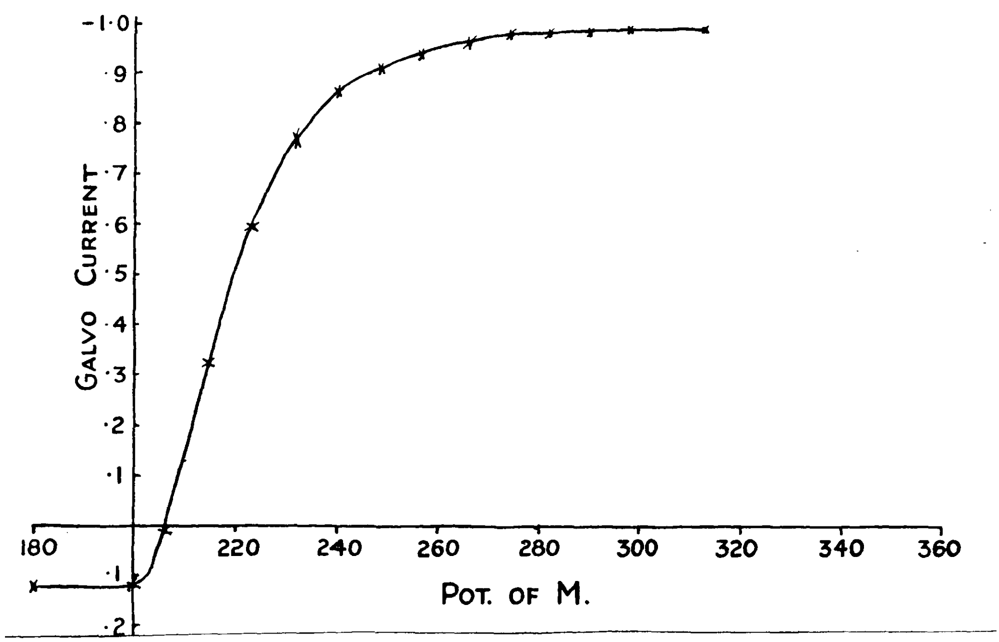
4. Electrical Connections:- The accelerating potential which energized the electrons and was applied between C and A was varied from 200 to 400 volts. In the actual experiments the cathode was maintained at -200 volts, but for the sake of clearness we shall suppose the cathode to be permanently earthed, and the potentials of all the other conductors increased by 200 volts. The anode A was in electrical contact with the walls of the ionization chamber and the electrode L, and consequently the potential of this anode system varied between +200 and +400 volts according to experimental conditions. The insulated electrode was used to detect the ionization current and also the electron current. Its potential could be varied between +500 and earth potential, and the same was true of the insulated electrode E. The heating current for the cathode C was supplied by four large accumulator cells, and a suitable series rheostat, capable of delicate adjustment, was included in the circuit. The electron current between A and C was of the order of 100 microamperes and was accurately indicated on a large-scale unipivot instrument. The electron current in the ionization chamber (about 1/100th of the total electron current) and the ionization current were measured by a sensitive galvanometer. This instrument could be changed over easily from measuring the current at M to measuring the current at E. The usual precautions were taken to avoid accidental leakage currents and

inductive effects.

Preliminary Experiments.

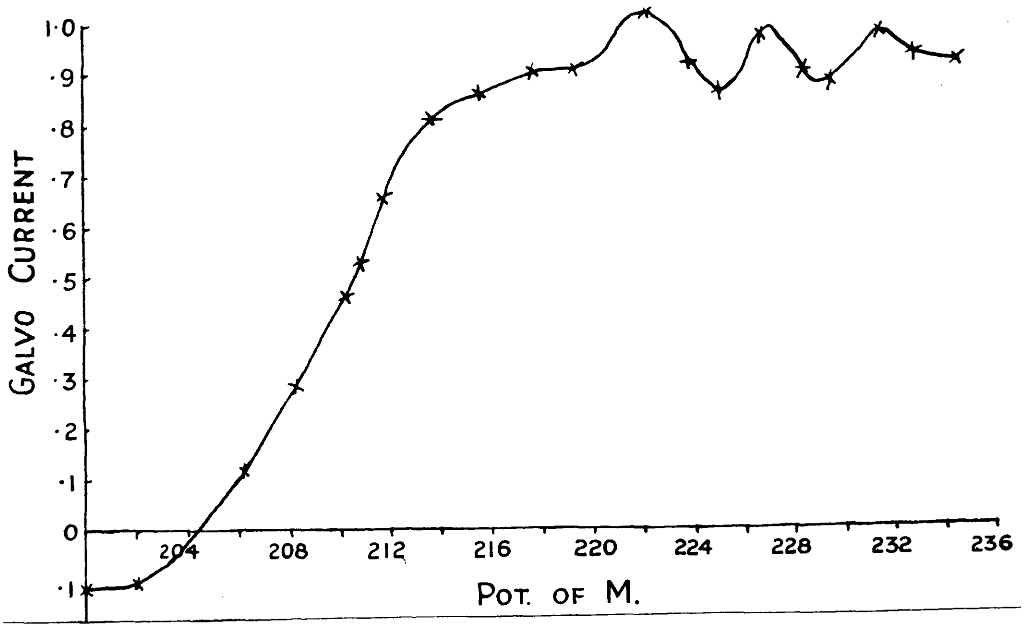
Owing to the nature of the vacuum apparatus, wax joints were necessary and baking-out was impossible. Yet, in order that tests should be carried out, it was necessary to obtain a very perfect vacuum (better than 0.0001 mm.) throughout the whole system. The outgassing of the cathode and anode surface required some days of overrunning, but eventually a stage was reached where the gas pressure could not be detected on the gauge when the apparatus was in action. Then the electron beam was produced, the accelerating potential being 200 volts, and readings were taken of the current at M with various potential differences across the ionization chamber. The curve in Fig. 18 indicates the mode of variation of the current with the potential at M. The rest of the ionization chamber was at +200 volts. The almost complete absence of kinks in the curve points to the

Fig. 18.



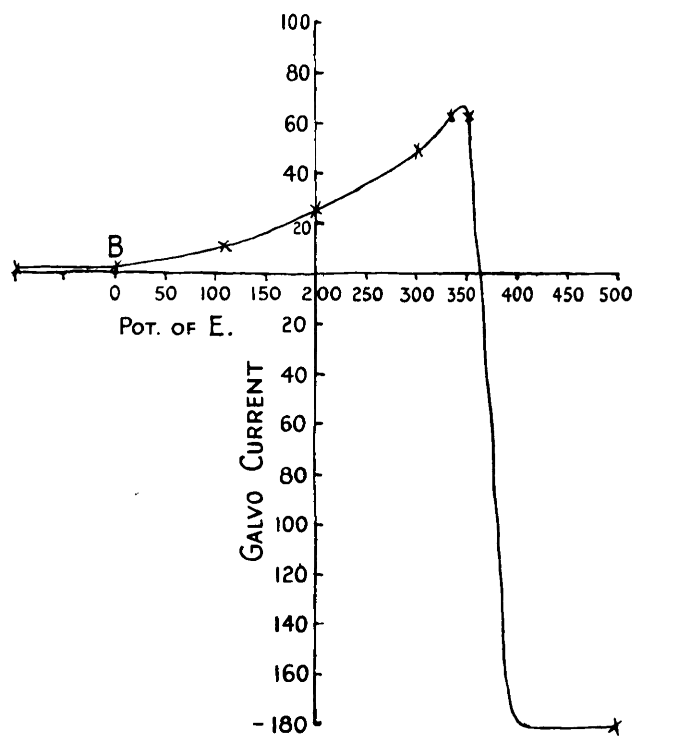
absence of gas in the apparatus, while the small positive current when the potential of M was negative with respect to the remainder of the ionization chamber is an indication of secondary electrons. It is surprising that the current became positive for such a small potential difference as 5 volts. Probably, however, the apparent electron current at this potential was due entirely to the balancing action of other secondaries emitted by parts of the chamber in the immediate vicinity of M. For comparison with Fig.18, the corresponding curve before outgassing is shown in Fig.19. Here a number of kinks due to the gas are in evidence.

Fig.19.



A second test experiment consisted in examining the velocity of the electrons emerging from the capillary anode when the whole apparatus was evacuated. For this purpose the electrode E was placed directly in front of the end of the capillary and about 2 mm. away from it. The accelerating voltage between A and C was 400, and the current of electrons to E was measured for different values of the potential difference between E and the anode. The results are shown in Fig.20, where the abscissa measures the potential of E in volts (V_E), the cathode as usual being assumed to be at earth potential, and the ordinate measures the current to E, in arbitrary units.

Fig.20.



From the graph it may be seen that all the electrons emerging from the anode were collected by E when V_E was greater than 400 volts (the fixed potential of the anode, V_A). When, however, V_E was less than V_A, some of the secondary electrons emitted by E were collected by A, thus causing a decrease in the electron current to E. As V_E was reduced, the current actually became positive, showing that the loss of secondaries from E was greater than the current of absorbed primaries. Gradually, however, as the energy of the primary beam on impact with E became smaller, (due to the increase in the retarding field between A and E) the number of secondaries per primary decreased, and, in consequence, the positive current to E also decreased.

Theoretically, the curve in Fig.20 should cross the potential axis again when V_E is between 0 and 10 volts, since no secondaries are emitted when the electron energy is small. The experiment failed to exhibit this phenomenon, however, the positive current to A persisting, even when V_E was negative. This was almost certainly due to the photoelectric action of the radiation from the incandescent cathode.

In this experiment the apparatus was evacuated to a gas pressure of less than 0.0001 mm. It was assumed that the electrons emerging from A had energy corresponding to 400 volts, and the curve of Fig.20 was assumed to be typical of this energy. It was therefore used for comparison with other similar graphs obtained at higher pressures when the energy of the electrons emerging from the capillary was not known.

Determination of the Energy Spent in Producing One Pair of Ions.

1. The Initial Electronic Energy (V):- The first step in determining the ionixing efficiency of the electrons was to find the energy of the beam as it entered the ionization chamber at a given gas pressure. In order that the electrons should be totally absorbed in the gas in the chamber, a relatively high gas pressure was necessary, and under these circumstances a considerable fraction of the energy of the beam was absorbed in the

capillary connecting tube. To measure this fraction, electrode E was brought into action, and curves similar to that in Fig. 20 were obtained for a large number of gas pressures. These were then compared with Fig. 20, and the voltage corresponding to B, where the electron current from E became very small and constant, was estimated as exactly as possible. Let this voltage be V_B. Then if the accelerating potential was 200 volts, V was 200 - V_B. If the accelerating potential was 400 volts, V was 400 - V_B. A continuous graph of V against the pressure (p) was not obtained, as the procedure was too elaborate, and it was difficult to maintain the pressure in the ionization chamber at a constant value when it was less than 0.01 mm. Figs. 21A and 21B, however, exhibit the variation of the potential V with the pressure within certain limits, the accelerating potential being 200 volts in (a) and 400 volts in (b). It was found that the pressure limits indicated were determined by experimental conditions. Higher pressures were impossible, since no electrons then penetrated to the ionization chamber, and lower pressures introduced considerable uncertainty as to whether all the energy of the electrons would be absorbed in the ionization chamber. From the readings which were obtained mean values of V at four pressures were estimated, and these four pressures were used in later observations. Table I shows results.

Fig.21A.

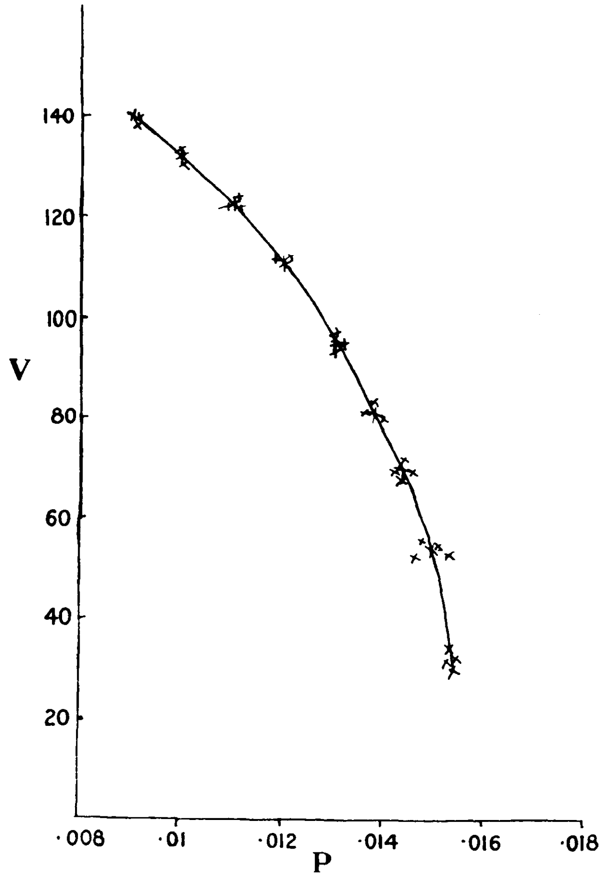


Fig.21B.

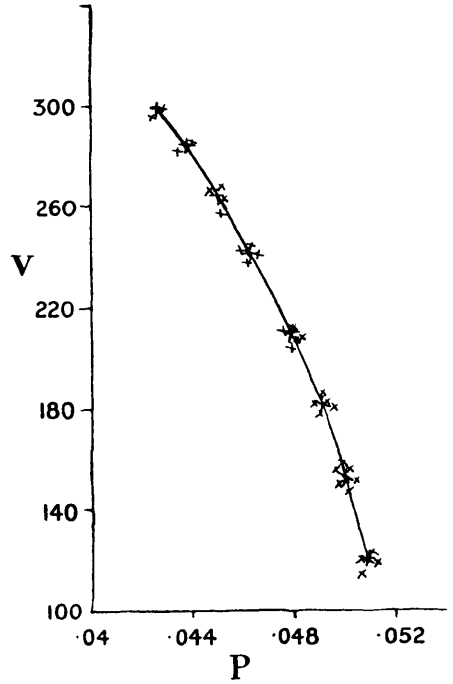


Table I.

Pressure. (mm.)	Accelerating Potential (volts).	V. (volts).
0.050	400	154
0.045	400	265
0.010	200	132
0.015	200	54

2. The Total Ionization Produced.- Having found the initial energy of the electrons in the four cases, it was now possible to determine the optimum electric fields to be applied across LM in measuring the ionization produced. In order that no recombination of ions should take place, it was necessary to keep the potential difference larger than a certain minimum. But 54-volt electrons are easily deflected, and it was necessary also to ensure that the beam did not impinge on one electrode before losing its energy.

The problem resolved itself into finding the minimum potential necessary to saturate the ionization current at pressures greater than 0.010 mm. and less than 0.050 mm. This was done in the usual manner. With an accelerating potential of 200 volts, and a pressure of 0.015 mm. , the potential of electrode M was varied from +200 to +150 volts, and the variation of the ionization current was observed. It was found that saturation took place with about 8 volts across LM, i.e. with electrode M at +192 volts. Since the potential required to produce saturation varies directly as the gas pressure, it was assumed that a potential difference of 10 volts would be sufficient for 200-volt electrons at a pressure of 0.01 mm. also. With an accelerating potential of 400 volts the same experiment was tried, the pressure being 0.05 mm. A higher saturation potential was found - about 16 volts - and it was decided to use 20 volts in the ensuing experiments under these conditions. Thus 10 - 20 volts was decided upon as a satisfactory saturation potential difference for 50 - 265 volt electrons.

The pressure was then adjusted to 0.01 mm. by means of the gas reservoir, and a steady electron current of 40 micro-amperes was produced, the accelerating potential being 200 volts. Electrode M was connected to +210 volts and the current measured. Then, by means of a commutator, the potential was changed rapidly to +190 volts, and the current again measured. These readings were repeated with the usual precautions. The same experiment was performed at the other pressures with the corresponding potentials, M being then connected to different potentials to produce the required fields. Table II gives the mean of the results obtained.

As the pressure and the accelerating potential were varied, the electron current in the ionization chamber also varied enormously. By varying the heating current in the cathode, however it was always possible to obtain a measurable current in the galvanometer. This adjustment was performed at random, with the result that the figures in the last column of Table II can only be used in pairs.

Table II.

Pressure. (mm.)	Potential of M. (volts)	V. (volts)	Current.
0.015	210	54	36.5
0.015	190	54	18.0
0.010	220	132	69.5
0.010	180	132	52.0
0.050	420	154	19.5
0.050	380	154	15.5
0.045	420	265	99.0
0.045	380	265	86.5

Results.

From the observations recorded in Table II, I and C can be determined. The current with M positive with regard to the remainder of the ionization chamber was I + C, while the current with M negative was C. Table III gives the energy required to produce one pair of ions for the four cases, using the formula

$$V_0 = (I/C)V.$$

Table III.

V	54	132	154	265
V_0	55.5	44.4	40.0	38.3

Discussion of Results.

The values obtained for V_0 indicate quite clearly a variation of the energy per ion pair with the initial velocity of the electron. This is in agreement with the fundamental theory, since the ionizing efficiency must be zero when the electron voltage is equal to the ionizing potential of the gas. Lehmann and Osgood[17] have shown that the total ionization N, produced in air by an electron of voltage V may be represented fairly accurately by the formula

$$N = k(V - 17) \quad \text{. . . . . (1).}$$

where k is a constant, the value of which was 0.0225 in their experiments, and 17 represented the ionizing potential of air. Although the results given in Table III of the present chapter are not in perfect agreement with such a formula, experimental errors are sufficient to account for the deviation. Fig.22 exhibits the mode of variation of N with V as calculated from the experimental results, and the best straight line drawn through the points. This line is

$$N = 0.0270(V - 17) \quad \text{. . . . . (2).}$$

and hence the value of k is considerably greater than that found in Lehmann and Osgood's investigation. The present value compares more favourably with Johnson's[17] formula,

$$N = 0.0275(V - 11) \ldots \ldots \ldots \quad (3).$$

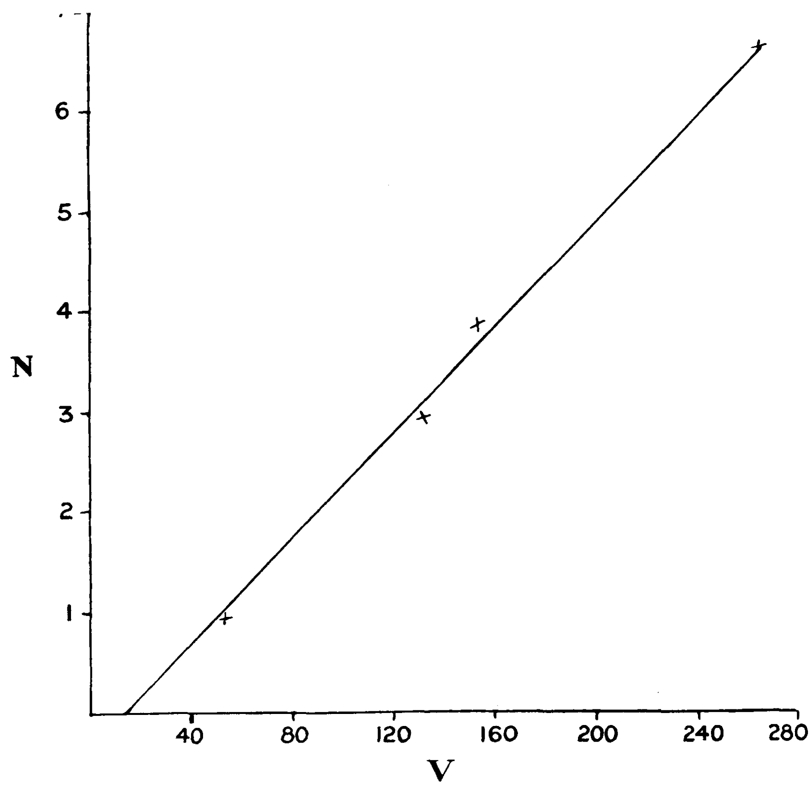
so far as gradient is concerned, but Johnson's intercept on the V-axis is much too small.

Assuming equation (2) to represent the present results, and writing it to give the energy required to produce one pair of ions, we have

$$V_0 = \frac{37}{1 - \frac{17}{V}}$$

so that when $V \to \infty$, $V \to 37$ volts. Such an extrapolation is not justifiable on the results of the present investigation, but it

Fig.22.



is possible to examine its validity in the light of other researches. Lehmann and Osgood found equation (1) to hold for values of V between 200 and 1000 volts. In a recent important paper Eisl[17] describes an investigation similar to those under consideration, but using electrons the accelerating potentials of which were from 5 to 60 kilovolts. Again, a linear relation between N and V is deduced, Eisl's result being

$$N = 0{\cdot}0311V \qquad (4)$$

The absence of the constant 17 in equation (4) is due, of course, to the large values of V employed. The important point to be noted is that a linear relation is characteristic of this very different electron velocity. Hence it may be safely assumed that, unless an abrupt discontinuity occurs in the N, V curve at some point between 1 and 5 kilovolts, an extrapolation from the present results is justifiable.

Yet the extrapolation does not lead to a satisfactory agreement between the various researches. Eisl's value of V_o for fast-moving electrons is given in his paper as $32 \pm 0{\cdot}05$ volts. The value deduced from the present experiments is 37 ± 2 volts. Lehmann and Osgood's result is 45 volts, the probable error being omitted. Eisl gives a table of the results found by various observers. These range from 26 - 45 volts, although the present writer is not certain that a comparison is useful, since different things were measured by the various observers.

Eisl's experiments appear to have been carefully carried out, and the discrepancy between his result and that found in the present investigation is difficult to explain. The higher the velocity of the electron the more difficult it becomes to collect all the ions produced along its path. Hence, so far as gas ionization is concerned, one might expect Eisl's result to be high rather than low. On the other hand, it is difficult to ensure that stray high-velocity electrons will not collide with metal surfaces in the ionization chamber. Such collisions would, of course, give rise to large numbers of secondary electrons, and there is no doubt that the work required to ionize a gas molecule is greater than the work required to liberate an electron from a metal surface. Hence, if sufficient precautions are not taken to ensure that the electrons lose all their energy in the gas, results for high-velocity electrons may be expected to be low. It is just possible that the discrepancy between Eisl's and the writer's results is to be attributed to this cause.

Correlation of Various "Constants".

Let N, V, k, have the meaning already assigned to them. Let R be the range of an electron travelling initially with a velocity corresponding to a potential V in air at atmospheric pressure, and let c be the ionization produced per unit path by an electron corresponding to V in air at the same pressure.

Then $$N = \int_0^R c\,dx$$

But by experiment $$N = k(V-17)$$

Therefore $$\frac{dN}{dx} = k\frac{dV}{dx} = -c \qquad (5)$$

For fast-moving electrons Whiddington's law states that

$$R = AV^2 \qquad (6)$$

This has been verified [18] for ranges between 0.1 cm. and 1.5 cm. in air at atmospheric pressure.

Let the range R_0 correspond to an initial voltage V_0. Then if x is measured from the point where the electron has energy V_0,

$$x = \frac{R_0}{V_0^2}\left(V_0^2 - V^2\right)$$

gives the relation between V and x.

Hence $$\frac{dV}{dx} = -\frac{V_0}{2R_0}\left(1 - \frac{x}{R_0}\right)^{-\frac{1}{2}}$$

Therefore by equation (5) $$C = \frac{kV_0^2}{2R_0V} \quad \ldots\ldots\ldots \quad (7)$$

This relation between c and V has been deduced from the two experimental laws expressed by equations (2) and (6), and only holds for the region over which these two laws are true. Equation (2) appears to be true for all values of V, but Whiddingston's law is meaningless when the initial energy of the electron is small. The range of an electron can only be measured algebraically along a straight line. The path of a slowly moving electron bears no relation to the range as measured.

As a consequence of this it would appear that $\frac{dN}{dx} = -c$ is also meaningless at low velocities. Yet c is a quantity which has been carefully measured by many observers for all initial electron velocities down to that corresponding to the ionizing potential of the gas.

Finally, it may be remarked that equation (7) is in good agreement with experiment for high initial electron energies.

Since the matter described in this chapter was published, a theoretical treatment of ionization in gases caused by cathode-rays has been given by E.J. Williams[41]. The latter's treatment is based on a voluminous paper by H. Bethe[42], and employs the new quantum theory. The theoretical estimate given by Williams of the energy spent per ion pair is that V_0 lies between the limits 2·2J and 3·2J where J is the ionization potential of the gas. The theory does not apply directly to the writer's experiments, since the range of electron velocities used in the work described above is precisely the range for which Bethe's approximations do not hold. The extrapolation which has been discussed, giving $V_0 = 37 \pm 2$ electron volts for fast-moving electrons, has, however, been shown to be justifiable, and for fast-moving electrons Williams' theory holds. If for J the value 17 volts is substituted (this being approximately the ionization potential of air), the theory leads to the inequality

$$37 \cdot 4 < V_0 < 54 \cdot 4,$$

so that the writer's experimental result is just within the range predicted by theory. If the experiments are to be trusted, the theoretical conclusion would appear to be that the efficiency of the more slowly moving electrons is comparatively large.

CHAPTER V.

THE HIGH FREQUENCY DISCHARGE. (THEORY).

Introduction.

The writer's attention was first drawn to the electric discharge at high frequencies, because the latter appeared to offer a means of obtaining discharge radiations without fear of the complications inevitably associated with the presence of electrodes immersed in the gas. It was, therefore, the discharge with external electrodes which he proposed to employ. Experiments with the production of such discharges soon convinced him, however, that external electrodes could only be used at very low gas pressures, so that the new technique was valueless for the continuation of the work described in chapters I, II and III. From the results obtained in these early researches he proposed a simple theory of high frequency gaseous conduction[19], and the purpose of his later experiments has been (and still is) to test this theory and to find out under what conditions it is valid. In the course of this work he has had to make a careful study of high-potential high-frequency discharge-tube technique; in particular, the problem of measuring the potential across a small capacity at ultra-radio frequency has been carefully investigated. As a result, he has invented a new form of thermionic voltmeter[20] which can be used at frequencies as high as 5.10^7/sec., and which even at that frequency absorbs a negligible fraction of the power available. The small capacity of the instrument should make it invaluable for investigations of the potentials across Lecher wire systems, and the writer proposes to use it for that purpose.

Historical:- The theory of the gas discharge between electrodes which are maintained at constant potentials is now well-known. The mechanism of the ionization in such a discharge consists of two processes, each of which has been thoroughly investigated. Ionization is produced (1) by the impact of negative ions on neutral molecules, and (2) by the radiations produced as a result of the neutralization of positive ions at the cathode. It is to Professor Townsend and his colleagues and assistants that our exact knowledge of the first process is due. His classical researches of the years 1900 to 1904 form a model of careful experimenting. It is to him also that the original mathematical theory of the discharge is due. But it is to the very much later work of Penning, Holst and Oosterhuis, and Taylor[21] that we principally owe our knowledge that positive ions do produce others at the cathode surface, and to the last of these that we are able to say definitely that the action at the cathode is in many cases at least photo-electric in character. It cannot yet be finally stated that the Townsend theory of ionization by the impact of positive ions on neutral molecules is wrong, but the work of these modern writers has shown that certainly other actions are in operation in the discharge.

As ever, Sir J. J. Thomson has contributed much to the broad ideas of all these researches, and has inspired the exact and painstaking experiments which have finally elucidated the mechanism of the discharge.

<u>The Electrodeless Discharge</u>:- It has been known for some considerable time that a discharge can be produced in a gas at low pressure by a high-frequency alternating potential, even if the latter is applied between electrodes outside the tube containing the gas. It has also been known for over thirty years that a Geissler tube placed inside a solenoid can be caused to glow when a high-frequency current flows in the latter. A casual examination of the electric and magnetic fields required under these circumstances to produce a discharge immediately showed that a gas was more easily ionized by a high frequency than by a direct field.

It was only in 1923, however, that a quantitive study of the discharge at high frequency was seriously begun, the first important papers on the subject being by Gutton [22],[23],[24]. Since then innumerable memoirs on the subject have been published, but, with the exception of Professor Townsend [25], no-one has made any real attempt to explain theoretically the quantitative results obtained. This is not surprising in view of the diversity of new facts which have come to light. To quote only one example which demonstrates the novelty of the phenomena exhibited, the following experimental facts from the writer's researches may be given.

(a). In a tube with internal electrodes, consisting of parallel plates 20 cm. apart, and containing hydrogen at a pressure of 0·001 mm. of mercury, it is necessary, using steady potentials, to produce a difference of 50,000 volts between the plates to start a discharge.

(b). In the same tube containing hydrogen at the same pressure, a bright discharge may be started with a peak potential difference of 365 volts at a frequency of 7.10^6/sec.

Conditions for the Ionization of a Gas by a High-Frequency Field.

Making the simplest possible assumptions, suppose a free electron to move under the action of an alternating electric field

then $$m\frac{d^2x}{dt^2} = Ee\cos\omega t\ ;$$

whence, if $x = 0 = \frac{dx}{dt}$, when $t = 0$,

$$\frac{dx}{dt} = \frac{E}{\omega}\frac{e}{m}\sin\omega t,$$

and $$x = \frac{E}{\omega^2}\frac{e}{m}\left(1 - \cos\omega t\right)$$

The assumption that $\frac{dx}{dt} = 0$ at $t = 0$ is, of course, an approximation; but since the velocity of agitation of an electron is of the order 10^6 cm./sec. at room temperature, and since the velocity producing ionization is of the order 10^8 cm./sec., the former may be neglected in comparison with the latter. Relativity corrections have also been neglected for similar reasons.

The electron will have acquired sufficient energy to ionize a gas molecule colliding with it at time t, if

$$\frac{1}{2}m\left(\frac{E}{\omega}\frac{e}{m}\sin\omega t\right)^2 > Ve, \qquad (1)$$

where V is a gas constant, related to the ionizing potential of the molecule. This is our first condition for ionization. The second condition must limit in some way or another the distance travelled by the electron while acquiring an ionizing velocity; for, should the electron collide inelastically with a molecule before attaining this velocity, or, conversely, should it not collide with a molecule until it had lost this velocity, then ionization would not in general occur. Writing this condition in the most general way to include the possibilities of a discharge at very low gas pressures,

$$\frac{Ee}{\omega^2 m}\left[2n+1+(-1)^{n+1}\cos(n+k)\pi\right] < L \quad \text{if } k < \tfrac{1}{2}, \quad \ldots \quad (2)$$

$$\frac{Ee}{\omega^2 m}\left[2n+1+(-1)^{n+1}\cos(n+k)\pi\right] > L \quad \text{if } k > \tfrac{1}{2}, \quad \ldots \quad (3)$$

where $\omega t = (n+k)\pi$, n is an integer, k is fractional, and L is a quantity proportional to the mean free path of the electron. These conditions state that when the electron is about to collide inelastically with a molecule, it shall be moving with the ionizing velocity. Condition (2) applies to the case where the speed of the electron is increasing, condition (3) to the case where the speed is decreasing. The limiting values of k are supposed to be determined from condition (1).

At low pressures yet another condition becomes operative. If L for the electron is greater than the length of the discharge tube, then, in order that the electrons should not be absorbed by the glass, the amplitude of the oscillations performed must be less than a certain length related in some way to the length of the tube, i.e.,

$$\frac{E}{\omega^2}\frac{e}{m} < l \quad \ldots\ldots\ldots \quad (4)$$

These four conditions are in themselves sufficient to define the electric field E and pulsatance ω, suitable for the production of ions at any pressure..

When a steady potential is applied across a volume of gas, the conditions for ionization of the gas are not the conditions for the production of the discharge. This is because the presence of the electrodes, associated with the steady electric field, cause the "life" of a gas ion to be very short indeed. The ions are destroyed very rapidly by neutralization at an electrode surface.

If, however, a high-frequency alternating potential is used, it is possible to adjust both the frequency and the field strength so that many of the ions formed will remain in the gas, oscillate to and fro, and will not be neutralized at an electrode. There are still losses, of course, due to recombination and diffusion, and it is impossible to adjust the conditions so that <u>no</u> ions meet an electrode. But, obviously, the rate of loss of ions may be very much diminished, so that it is just possible that the condition for ionization may be an approximate condition for a discharge.

If the electrodes and walls of the tube are at an infinite distance from the volume of gas under consideration, conditions (1) and (2) are sufficient for a discharge.

I;- The simplest case governed by these inequalities is where one-half the amplitude of oscillation of a free electron under the influence of the electric field is greater than its mean free path. Writing this mathematically, we have

$$\frac{E}{\omega^2}\frac{e}{m} > L \quad \cdots \quad (5)$$

Where this condition is fulfilled, equations (1) and (2) become

$$\frac{E}{2\omega^2}\frac{e}{m}\sin^2\omega t > V \quad \cdots \quad (1')$$

and

$$\frac{E}{\omega^2}\frac{e}{m}(1-\cos\omega t) < L \quad \cdots \quad (2')$$

Eliminating ωt between these two conditions, and remembering that $\omega t < \frac{\pi}{2}$, the new condition

$$E > \frac{V}{L} + \frac{L\omega^2}{2\frac{e}{m}} \quad \cdots \quad (6)$$

is obtained. Write $\omega = 2\pi\nu$, where ν is the frequency of the oscillation, and $L = K/p$, where p is the gas pressure; then

$$E > \frac{Vp}{K} + \frac{2\pi^2\nu^2 K}{p\,\frac{e}{m}} \quad \cdots \quad (6')$$

This inequality contains both of the previous conditions. It defines the field strength required to produce ionization in terms of the pressure of the gas, the frequency of the applied potential and constants.

Along with this condition must be taken the equally important inequality (5) which becomes

$$E > \frac{4\pi^2\nu^2 K}{p\,\frac{e}{m}} \quad \cdots \quad (5')$$

If E is the minimum field-strength required to start a discharge

$$E = \frac{Vp}{K} + \frac{2\pi^2\nu^2 K}{p\,\frac{e}{m}}$$

Taking this with (5'), we obtain

$$\frac{Vp}{K} \geq \frac{2\pi^2\nu^2 K}{p\,\frac{e}{m}}$$

or

$$p \geq \pi K\nu\sqrt{\frac{2}{V\frac{e}{m}}} \quad \cdots \quad (7)$$

II:- Consider now the case where $\frac{\pi}{2} < \omega t < \pi$.

Then the conditions for ionization are $\frac{\pi}{2} < \omega t < \pi$

$$\frac{E^2}{2\omega^2}\frac{e}{m}\sin^2\omega t > V$$

and

$$\frac{E}{\omega^2}\frac{e}{m}(1-\cos\omega t) > L \quad \cdots \quad (2'')$$

which again give condition (6') as the eliminant, remembering that $\cos\omega t$ is negative. In this case, however,

$$\frac{E}{4\pi^2\nu^2}\frac{e}{m} < L < \frac{E}{2\pi^2\nu^2}\frac{e}{m}$$

are the auxiliary conditions. The first of these, taken along with (6'), gives

$$\frac{Vp}{K} < \frac{2\pi^2\nu^2 K}{p\frac{e}{m}}$$

or

$$p \leq \pi\nu K\sqrt{\frac{2}{V\frac{e}{m}}}$$

Thus the conditions for the ionization of a gas by a high frequency electric field reduce to a single equation, connecting the field-strength with the gas pressure, the frequency of the applied potential and constants. This equation (for an infinite volume of gas) holds for any pressure and any frequency. Let it be called the "characteristic equation" for the high frequency discharge, and written

$$E = \frac{Vp}{K} + \frac{2\pi^2\nu^2 K}{p\frac{e}{m}}$$

<u>Examination of the Characteristic Equation</u>:- Let approximate values of the constants be inserted in the equation, imagining the gas to be hydrogen,

then $V = 17$ volts, $\frac{e}{m} \doteq \frac{e}{m_0} = 1{\cdot}77.10^7$, $K = 0{\cdot}121$ (p in mm. of mercury).

Therefore $$E = 1{\cdot}40.10^{10}p + 1{\cdot}35.10^{-7}\frac{\nu^2}{p}$$

Writing E in volts per cm., $\mathcal{E}$ say,

$$\mathcal{E} = 140p + 1{\cdot}35.10^{-15}\frac{\nu^2}{p}$$

In Fig. 24 the curve given by this equation is drawn from $p = 1{\cdot}0$ mm. downwards for the frequency 10^7/ sec.

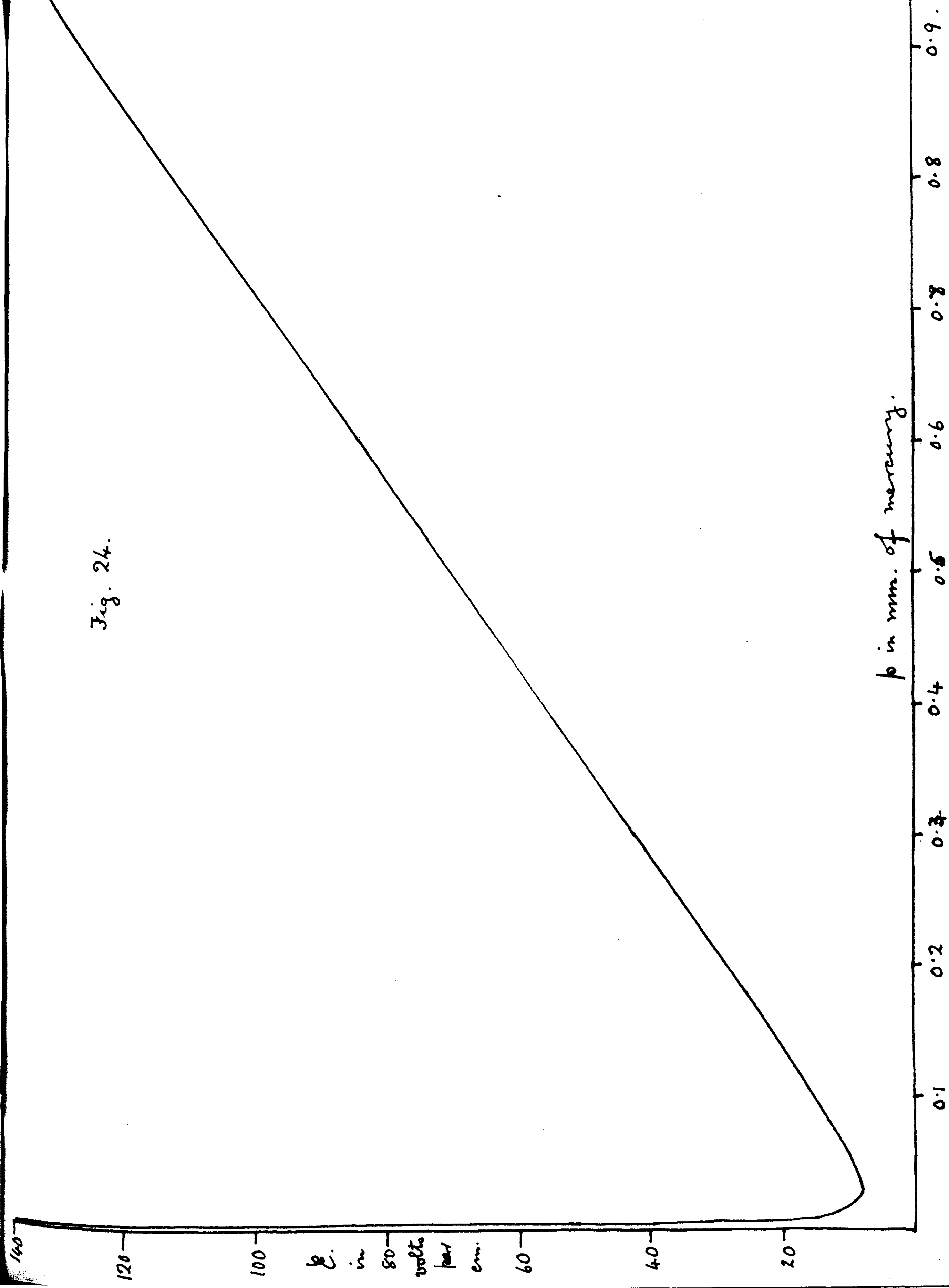


Fig. 24.
p in mm. of mercury.
0.1
0.2
0.3
0.4
0.5
0.6
0.8
0.9
E in volts per cm.
20
40
60
80
100
120
140

It is obvious from the value of the coefficient of $\frac{\nu^2}{p}$ that the curve will not be very much different for different values of ν over the greater part of its range. At $p = 1$ mm., if $\nu = 10^5$, $\mathcal{E} = 140 \cdot 00$; if $\nu = 10^7$, $\mathcal{E} = 140 \cdot 14$; the difference is about 0·1%. Hence at high pressures the frequency of the applied electric field is of no importance.

The case is quite otherwise at low pressures. At $p = 0 \cdot 001$ mm., if $\nu = 10^5$, $\mathcal{E} = 0 \cdot 1535$; if $\nu = 10^7$, $\mathcal{E} = 135 \cdot 14$. Increasing the frequency, as is to be expected, has considerably increased the field required for ionization.

To obtain a more definite idea of the value of the characteristic equation it is necessary to compare the mean free path of the electron at any pressure with the amplitude of its free oscillation - $\frac{\mathcal{E}\frac{e}{m}}{2\pi^2\nu^2}$. Assuming that the electron has a negligible diameter compared with that of the gas molecule, and is moving much more rapidly, its mean free path may be calculated by the methods of the Kinetic theory of gases. For hydrogen this leads to the formula $L = 0 \cdot 121/p$, where p is in mm. of mercury. This is the formula which has already been used. The amplitude of oscillation of the free electron becomes A, where

$$A = \frac{8 \cdot 97 . 10^{13} \mathcal{E}}{\nu^2}$$

In order that the theory given should hold, A must be greater than L, and this leads to the following Table.

Table I.

ν	10^5	10^6	2.10^6	10^7
Minimum p	$\frac{\cdot 0000135}{\mathcal{E}}$	$\frac{\cdot 00135}{\mathcal{E}}$	$\frac{\cdot 0054}{\mathcal{E}}$	$\frac{\cdot 135}{\mathcal{E}}$

The pressure must not be less than that given in the lower row of the Table.

In no case examined by the writer, or discovered by him in the researches of others, have the relations between pressure and electric field strength been such as to violate the condition L< A when the discharge was initiated. On the other hand the field required to maintain a glow is often such that L is greater than A, and it is therefore of interest to examine the conditions for ionization in such circumstances.

III:- $\pi < \omega t < \frac{3\pi}{2}$

In this case the fundamental condition (2) becomes

$$\frac{3E\frac{e}{m}}{\omega^2} + \frac{E\frac{e}{m}}{\omega^2}\cos\omega t < L$$

with the auxiliary conditions

$$\frac{2E\frac{e}{m}}{\omega^2} < L < \frac{3E\frac{e}{m}}{\omega^2} \qquad \ldots\ldots (8)$$

Hence,

$$\cos^2\omega t > 9 - \frac{6\omega^2 L}{E\frac{e}{m}} + \frac{\omega^4 L^2}{E^2\left(\frac{e}{m}\right)^2}$$

Condition (1) is

$$\sin^2\omega t > \frac{2V\omega^2}{E^2\frac{e}{m}}$$

Therefore eliminating ωt as usual

$$1 > 9 - \frac{6\omega^2 L}{E\frac{e}{m}} + \frac{\omega^4 L^2}{E^2\left(\frac{e}{m}\right)^2} + \frac{2V\omega^2}{E^2\frac{e}{m}}$$

This may be written

$$E > \frac{1}{L}\left(\frac{V}{3} + \frac{4E^2\frac{e}{m}}{3\omega^2}\right) + \frac{L\omega^2}{6\frac{e}{m}}$$

to obtain an inequality of the same form as the "characteristic equation".

But from condition (1)

$$\frac{4E^2\frac{e}{m}}{3\omega^2} > \frac{8V}{3}$$

Therefore E must certainly be greater than E'

where $$E' = \frac{3V}{L} + \frac{L\omega^2}{6\frac{e}{m}} \qquad \ldots\ldots (9)$$

As was to be expected, the ionizing electric field is about three times as great as in Cases I and II at high pressures. At low pressures, however, where L is large, the ionizing field is about 1/3^rd of its value in the simple case.

It may be remarked here that the writer has observed that it is difficult (and sometimes almost impossible) to extinguish a glow in a discharge tube at very high frequency and very low gas pressure by reducing the applied voltage. It is usually possible, however, to stop the discharge by increasing the voltage beyond a certain point and then decreasing it suddenly. This is remarkable evidence that the physical processes described by the analysis of Case III actually take place once the glow has been started. It must be noted, of course, that equation (9) is not of the exact nature of the "characteristic equation". For ionization to occur when the electron is moving back along its path E must certainly be greater than E'. How much greater could only be obtained by a complicated calculation for each pressure and frequency.

Finally it is necessary to justify the writer's choice of initial conditions so that the electron velocity is zero when the electric field strength is a maximum. The justification lies in the consideration of the motion of an electron which does not fulfil the chosen initial conditions. If $x = 0 = \frac{dx}{dt}$ when $t \neq 0$, the electron drifts out of the field unidirectionally, and this is almost equivalent to the action of a steady potential difference. Hence electrons, the velocities of which are not approximately zero when the field is a maximum, are soon neutralized at an electrode if they do not collide with gas atoms, and an analysis of their motion also shows that their ionizing efficiency is smaller. The conditions chosen are artificial to the extent that only a few electrons in the gas will at any time fulfil them, but it will be shown later that it is exactly those electrons which initiate the discharge.

Experimental Verification of the Theory.

Figs. 25 and 26 below are reproduced from an important paper by Kirchner[26] on the High-frequency discharge. They represent

Fig. 25.

Oxygen.

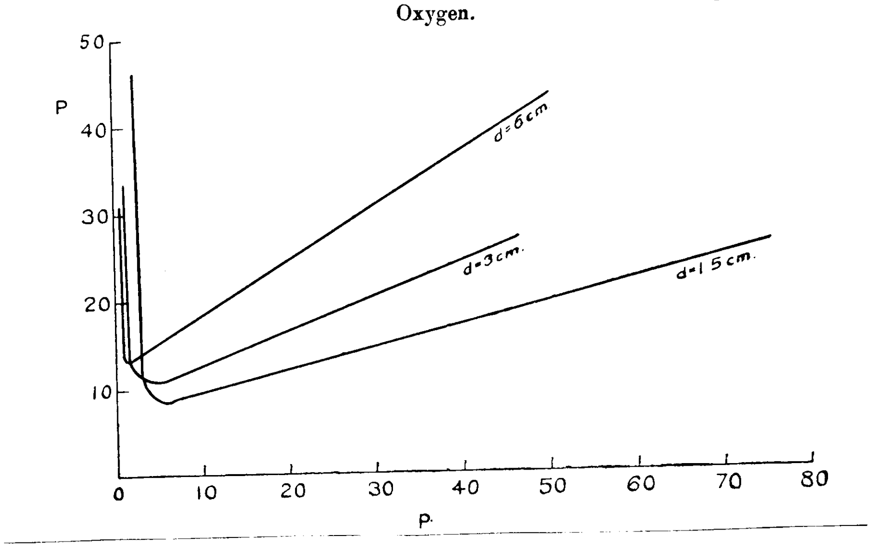
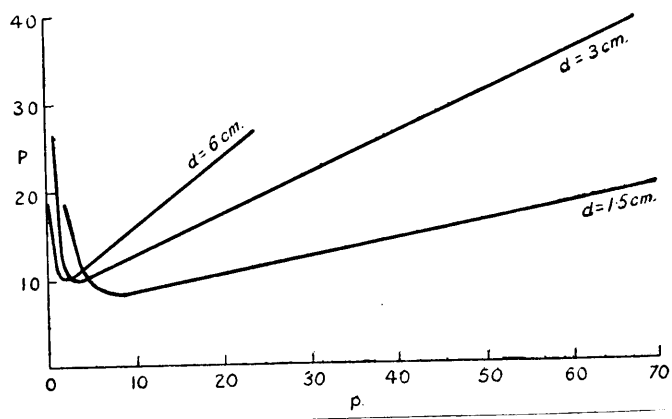


Fig. 26.

Air.



the mode of variation with the gas pressure of the potential difference (P) which must be applied between electrodes d cm. apart in order that a glow discharge may just be maintained. In the figures P is measured in arbitrary units.

Now it is obvious that the conditions of Kirchner's experiments, where the gas under investigation was contained between two parallel plate metallic electrodes at most 6 cm. apart, do not correspond to the infinite mass of gas which has so far been considered. But it is interesting to note that the forms of the p,P curves shown are similar to that of the p,$\mathcal{E}$ curve of Fig. 24, and that there is little or no doubt that an equation to fit any of Kirchner's curves would be of the general form

$$P = Ap + Bp^{-n},$$

where A and B are constants, and n is positive. The oscillation frequencies used by Kirchner were of the order 10^7/sec., and the theory which has been given holds when the amplitude of oscillation of a free electron (and its mean free path) is small compared with the distance between the electrodes. A specific case taken from Kirchner's paper is for $\nu = 3\cdot5.10^7$/sec., where the minimum $\mathcal{E} = 15$ volts/cm. The corresponding electron amplitude of 11 cm. is considerably greater than the maximum distance between the electrodes, so the theory given above will not apply even approximately at low pressures.

This research has been taken as an example of the fact that it is difficult to obtain results which can be applied directly as a test of the theory. Nevertheless it is suggestive that Kirchner's P,p curves are of the general form demanded by the characteristic equation.

In the same class as Kirchner stand most of the investigators of the discharge - notably Professor Townsend and his collaborators[27, 28, 29, 30, 31, 32]. While their results are of the first importance and great general interest, the phenomena under investigation are too complex for a tentative mathematical explanation.

Quite otherwise is it with the outstanding researches of MM. C. and H. Gutton[23, 24] and J. Brasefield[33, 34, 35]. A paper by the former authors entitled "Sur la décharge électrique en haute fréquence[24]" is particularly notable, and appears to the writer to elucidate the mechanism of the glow considerably, if taken in conjunction with the above theory. The Guttons used a cylindrical discharge tube 10 cm. long and 3 cm. in diameter with external parallel plate electrodes of tin foil sealed to the flat ends of the tube. The filling gas was hydrogen. They varied the frequency of the applied E.M.F. between $5{\cdot}33.10^4$/sec. and $9{\cdot}6.10^7$/sec. - a particularly wide range - and measured the starting potential of the discharge ("sparking potential") as a function of the gas pressure for 16 frequencies in the range. Their results are shown in Fig. 27 taken from their paper, the numbers on the curves being the wave-length of the oscillation (λ).

The following points are worthy of notice.

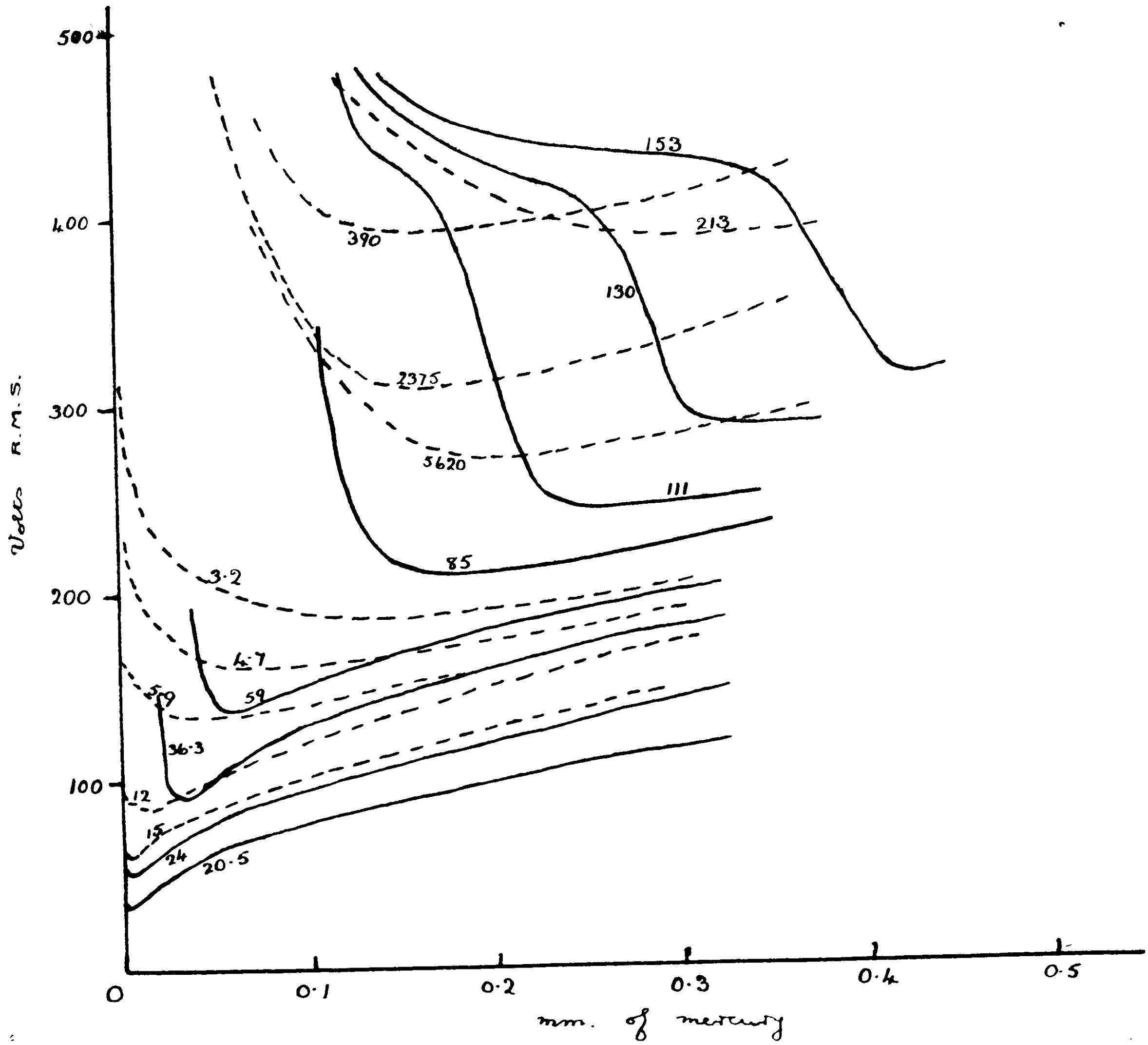
I. The majority of the curves may easily be fitted to the equation

$$\mathcal{E} = Ap + \frac{B}{p}$$

II. Three different régimes are in evidence

(a) $\lambda = 560$ m. to $\lambda = 213$ m.

Fig. 27.



500
400
300
200
100
0
0·1
0·2
0·3
0·4
0·5
Volts R.M.S.
mm. of mercury
153
213
390
130
2375
5620
111
85
3·2
4·7
59
5·9
36·3
12
15
24
20·5

(b) $\lambda = 153$ m. to $\lambda = 20\cdot5$ m.

(c) $\lambda = 15$ m. to $\lambda = 3\cdot2$ m.

In (a) and (b) the relations between frequency and electric field strength are such that our theory does not apply directly. In (c), where the minimum $\mathcal{E} = 6$ volts/cm. and the minimum $\nu = 2.10^7$/sec., the important amplitude of free electronic oscillation (at minimum starting potential) is 1·35 cm. This is small compared with the length of the tube, and therefore our theory should apply.

<u>The theory is confirmed in every point</u>.

(i). The curves are of the correct form

$$\mathcal{E} = Ap + \frac{B}{p}$$

(ii). As ν increases $\mathcal{E}$ increases <u>p</u> remaining constant, but for <u>p</u> large the effect of ν is small.

(iii). The minimum on the $\mathcal{E}$,p curve is given by the theory as

$$E_m = 2\pi\nu\sqrt{\frac{2V}{\frac{e}{m}}}\,, \qquad p_m = \pi\nu K\sqrt{\frac{2}{V\frac{e}{m}}}$$

From the Guttons' curves, E_m increases as ν increases and p_m increases as ν increases. No more conclusive evidence of the essential validity of the theory could be desired.

It is hardly necessary to consider further experimental evidence, but, remembering how complicated the phenomena are at lower frequencies, it may be well to refer briefly to the work of J. Brasefield. In a paper entitled "The Conductivity of a High Frequency Discharge in Hydrogen[34]" he too gives curves connecting the E.M.F. across the discharge with pressure at various frequencies. In his experiments the cylindrical discharge tube was 90 cm. long and 4·5 cm. in diameter, and the electrodes were concentric external cylinders of width 4 cm. He found that the conductivity could be measured most accurately when the inter-electrode distance was 40 cm. He measured the E.M.F. required to produce a conduction current (as distinct from a capacity current) in the tube of 100 milliamps. so that again it is not correct to apply the theory directly. However, he too obtains curves of the standard type, and he too finds that the electric field necessary to produce the required current increases when the frequency is increased from $1\cdot5.10^7$/sec. to $2\cdot0.10^7$/sec. Beyond this frequency he did not go. For frequencies less than $1\cdot5.10^7$/sec., the fields increased with decreasing frequency at low gas pressures, the writer's explanation being, of course, that the amplitude of free oscillation of the electrons was then too large.

A later paper by Brasefield[35] describing work with similar apparatus show very clearly the effect of the electrodes at lower frequencies. In these later experiments he varied the distance between the electrodes, keeping the gas pressure and oscillation frequency constant. He then assumed that the E.M.F. across the tube would be made up of two components,

(i) the drop of potential at the electrodes

(ii) the product of the electric field strength in the gas and the inter-electrode distance.

Thus if V is the potential difference across the tube,

$$V = V_0 + Ed,$$

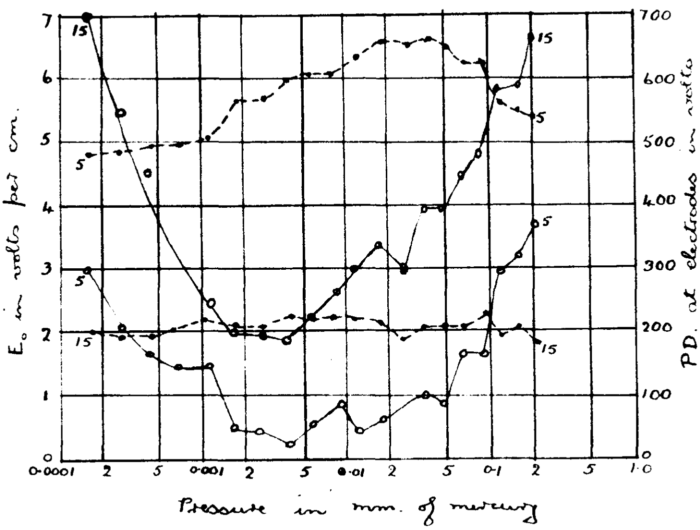
where V_0 is (i) and E.d is (ii).

By measuring V for different values of <u>d</u> he deduced E.

In this way he obtained curves connecting E with p and V_o with p for various frequencies. A typical result for mercury vapour is shown in Fig. 28.

Fig. 28.

The full line represents E.



The broken line represents V_o.

The numbers on the curves represent the frequencies at which they were taken divided by 10^6. The important point to be noted is that the elimination of the potential drop at the electrode has exhibited the fact that a stronger electric field is required for ionization as the frequency increases even at the comparatively low frequencies used.

Hence the theory which holds for the total potential difference across the discharge at very high frequencies also holds for the electric field in the gas at lower frequencies. This suggests that the natural theoretical development is along the lines of calculating the potential drop at the electrodes in terms of the oscillation frequency. The final form of the characteristic equation, taking account of the electrode drop (cathode fall) is suggested by Brasefield's curves. It is probably of the form

$$V = V_0 e^{-kd} + \alpha \mathcal{E}$$

where V_0 is the normal cathode fall, k is positive, d is the distance between the electrodes and $\mathcal{E}$ is given by the former "characteristic equation".

Conclusions.

The conclusions to be drawn from the work described in this chapter are tentative only. It would appear that the writer's theory of the discharge applies in practice only to a limited range of very high frequencies. If, of course, it were possible to use larger tubes and higher potential differences, the theory would apply for lower frequencies. Within the proper range the theory is completely verified by the researches of Gutton and Brasefield, and it also appears probable that the mode of variation of the potential difference across the discharge with the pressure, the frequency remaining constant, is given correctly by the theory outside of the range to which it properly applies. Further evidence could, of course, be adduced to verify these conclusions, but what has been given is probably sufficient.

CHAPTER VI.

THE HIGH-FREQUENCY DISCHARGE (EXPERIMENTAL).

INTRODUCTION.

In this chapter the writer's experimental studies of the discharge will be described. These are still in progress so that the account is by no means a finished one. The chapter is divided into two parts. In Part I the technique of high-frequency discharge-tube work is discussed. The subject is so full of pit-falls and difficulties that useful experiments can only be performed when great care is taken to eliminate disturbing factors and many memoirs which have already been written are of little value because the authors did not appreciate the importance of these factors. In Part II the principal results obtained by the writer are described and partly discussed.

PART I.

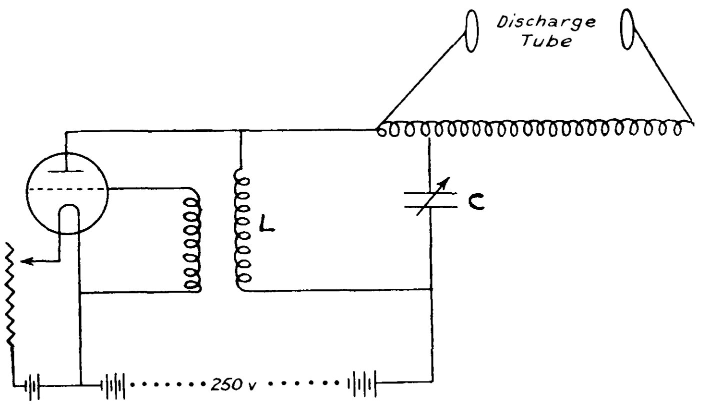
Technique.

The Application of the Tesla Transformation to the Production of High-Frequency Discharges.

As has already been mentioned, the writer's first experiments aimed at the production of high-frequency discharges at relatively high gas pressures. To obtain this object it was obviously necessary to produce high potentials across the discharge, and therefore some efficient high-frequency step-up transformer was indicated. The circuit which was finally used is shown in

Fig. 29.

Fig. 29.



The high-frequency current was produced by means of the normal triode oscillator circuit, using four Marconi T 15 valves in parallel. The ratio L/C was made as small as possible (consistent with efficient working of the triode) so that large currents were generated in the circuit LC, which included the bottom four of five turns of a Tesla Coil. The latter consisted of about 130 turns of copper wire (16 B.W.G.) of radius 15 cm., the turns being about 1 cm. apart. As was to be expected, a large potential difference was generated across the whole coil. By means of the condenser C the frequency of the driving oscillations could be varied, and it was found that the Tesla Coil exhibited an exceedingly sharp resonance peak. Consequently a fine variation of the capacity C controlled the potential difference across the coil without seriously affecting the frequency.

The discharge-tube used in the experiment was a cylindrical tube about 20 cm. long with a spherical end bulb of about 15 cm. diameter. The diameter of the cylindrical portion was 4 cm. The electrodes were two bands of tin foil wrapped round the tube; the distance between these could be varied.

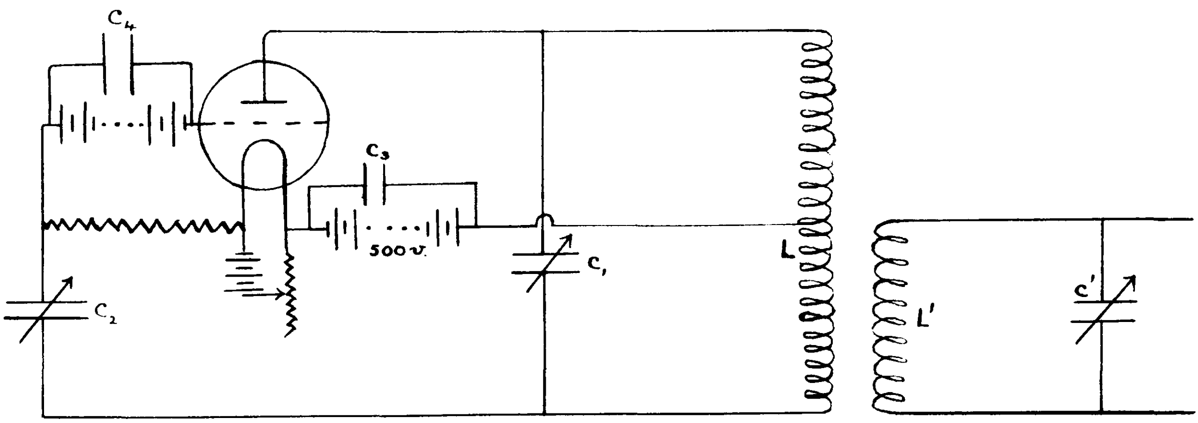
Bright discharges were obtained with this arrangement at pressures ranging from 0·01 mm. to 10 mm. of mercury. At higher pressures (more than 0·1 mm.) the glow was of the symmetrical striated type described by Richards[36], but at lower pressures the plasmoidal discharges recorded by Wood[37], Tonks[38] and Langmuir[39] were observed. In many cases the glow extended beyond the electrodes into the bulb at low pressures. The filling gas was hydrogen.

This appears to be a very suitable means of producing high potentials for discharge-tube work at a frequency of 10^6/sec. The peak voltage obtained in these experiments was of the order 4000. This could doubtless be improved upon. The method is not useful at higher frequencies, as the distributed capacity of the Tesla Coil is considerable. To raise the natural frequency of the coil to, say, 10^7 would require an unwieldy piece of apparatus.

<u>Oscillator for Quantitative Investigation of Potential and Frequency</u>:- The experiments described in the previous section were performed in 1929. When the writer returned to the subject in 1931 his aim was entirely different, being, indeed, to measure accurately the potentials required to initiate H.F. discharges at various frequencies and gas pressures. For this purpose the oscillator shown diagrammatically in Fig. 30 has been found very suitable, provided that the frequency is less

than 10^7/sec. It may be altered slightly to function at very much higher frequencies. In the oscillatory circuit the ratio L/C, was kept as small as possible. The anode tap was adjusted for maximum efficiency. Plug-in coils were used in both portions of L, so that different sets of coils gave different frequencies.

Fig. 30.



It is very necessary in H.F. discharge-tube work to avoid having even a small direct E.M.F. across the tube. Hence L was coupled electromagnetically and very loosely to another circuit L′C′, and leads were taken from the terminals of C′ to the discharge-tube. In the second circuit the ratio L′/C′ was large in order to produce a large potential difference across C′. On the other hand C′ was not made as small as it might have been for reasons which will appear later.

The circuit had to be so adjusted that a uniform change in the potential difference across C′ could be brought about without changing the frequency of the oscillations. It was found that this could only be done by varying the valve filament current, and since a Philips-Mullard 40 watt transmitting valve was employed, requiring a filament current of 2 amperes, this was not easy. Ultimately, a finely adjustable rheostat was obtained which gave accurate control of the power available. The value of the grid-biassing battery was then found for which the grid current was as small as possible. This ensured (a) that the output of the oscillator was a sinusoidal wave, and (b) that the frequency did not vary appreciably with change in the filament current (See D.F. Martyn, "Frequency Variations of the Triode Oscillator"[40]). Since the value of the capacity C_2 determined the coupling between the grid and anode coils, maximum efficiency and minimum frequency change with change of filament current could always be obtained. The condensers C_3 and C_4 (both $1\mu F$) provided low impedance paths for the high frequency oscillations.

<u>The Measurement of the Frequency:</u>- This presented no difficulties. The measurement was carried out with a General Radio Co. Standard Short-Wave Meter of range 240 - 20 metres. At higher frequencies a Lecher Wire system was employed.

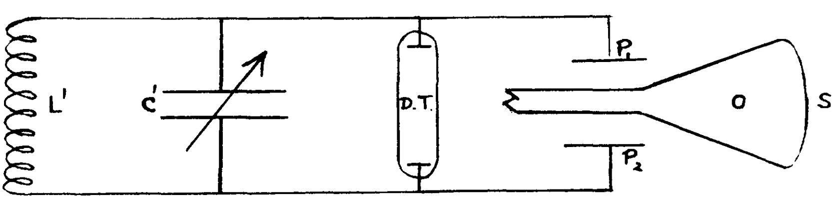
<u>The Measurement of the Potential Difference across the Condenser C'</u>

Much has been written with regard to the measurement of high-frequency potential differences, but it cannot be said that the measurement is an easy one even at this date. So long as normal radio-frequencies ($< 5.10^6$) are used, and so long as the potential is relatively small, an accurate and reliable instrument is to be found in the Moullin Thermionic Voltmeter. For high voltages, however, and high frequencies, the latter is of little value.

The writer began his experiments with an attempt to use a quadrant electrometer idiostatically. The absolute calibration of this instrument is comparatively simple, and by suitably choosing the needle suspension the desired sensitivity can be obtained. The principal objection to the electrometer is its variable capacity. Even with the most efficient damping of the needle oscillations, the natural frequency of the circuit in which the measurement is being made varies with the voltage, and at high frequencies where the electrometer capacity is a considerable fraction of the total circuital capacity this variation makes tuning an impossibility. The electrometer even in a modified form had to be abandoned.

The attempt was then made to use a Cathode Ray Oscillograph as the measuring instrument. Two standard forms of the instrument were tried, and in both it was found that it was impossible to use the internal deflecting plates. These oscillographs are meant to be used for the measurement of small voltages. It was impossible to reduce the sensitivity to the desired value and yet obtain a bright sharp spot on the phosphorescent screen. External electrodes were then used with some degree of success. By this means the sensitivity was reduced, and, in addition, the capacity of the condenser formed by the deflecting plates. Fig. 31 shows the circuit employed.

Fig. 31.



The discharge-tube (D.T.) and deflecting plates (P_1, P_2) were in parallel with the capacity of the coupled circuit. As has already been mentioned, C' was deliberately made reasonably large, so that the capacities of the tube and deflecting plates should be small in comparison.

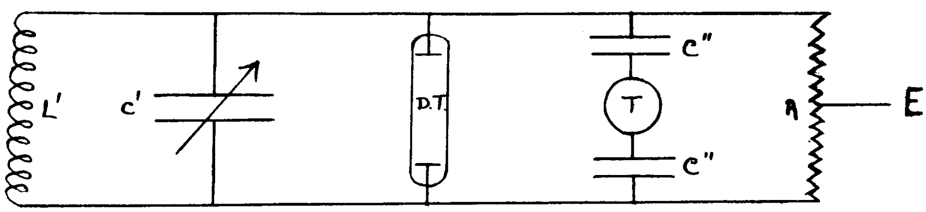
From the theory of the oscillograph it follows that the length of the line on the phosphorescent screen S is directly proportional to the voltage across $P_1 P_2$. Hence comparative readings of the voltage applied to the tube could be obtained directly, and this mode of procedure has many advantages. It is open to two objections, one of which becomes fatal at high frequencies. In the first place the diameter of the screen is only about 12 cm., and it is difficult to measure the length of a line on it with any greater accuracy than that given by a common foot-rule. This means that the minimum probable error is of the order of 1%, while it may be as great as 10%. In the second place measurements cannot be made at high frequencies, because an electrodeless discharge takes place in the oscillograph itself. The latter is filled with argon to a pressure of about 0·008 mm., this being necessary to prevent spreading of the electron beam. At this gas pressure high-frequency discharges take place very readily.

Even at lower frequencies the instrument is not entirely suitable, because it is difficult to calibrate it accurately. Alternating current must be employed, since the deflecting plates are outside the tube, and it is difficult to ensure that the sensitivity remains constant over a long period, since it depends upon the potential difference accelerating the electron beam. Nevertheless many useful measurements of a preliminary nature were taken with this instrument. It was only abandoned when exact absolute values of the potential were required.

It was at this point that the writer became interested in the design of a new thermionic voltmeter for use at high frequencies and high potentials. The description of this instrument and the experiments performed with it are given in Chapter VII.

For general utility and reliability the condenser and vacuum thermocouple circuit was found to be best for discharge-tube measurements. The circuit employed is shown in Fig. 32.

Fig. 32.



In place of the deflecting plates used with the oscillograph, the condensers and thermocouple are employed. C" represents two equal condensers of small capacity (usually about $4.10^{-7}\mu F$), the thermocouple (Standard Cables) being placed at the potential node between them. The effective capacity of these condensers was always small compared with C', so that the tuning was not affected. The thermocouples were of the centre-connected type, the heater wire being connected at its mid-point to the thermo-junction. A Cambridge unipivot galvanometer of suitable resistance measured the thermo-electric current.

This method of measuring large potential differences at frequencies of the order of 10^7/sec. is very reliable. It suffers from the disability that practically all thermo-junctions show a considerable time-lag, and that direct readings of the potential are impossible. But with these limitations it forms perhaps the most successful technique for discharge measurements, when cautiously used. One difficulty encountered was the tendency of the thermo-junction to pick up stray oscillations by means of its self-capacity. This can easily be eliminated by care in the disposition of the various components of the oscillator. The behaviour of the instrument is much improved by the inclusion of the parallel large resistance R (about 2.10^5 ohms) with a centre-tapping to earth.

<u>The Measurement of the Potential Difference Necessary to Initiate a Discharge</u>:- For this measurement there is only one satisfactory <u>modus operandi</u>. The potential across C' is slowly increased, the readings of the thermo-couple galvanometer being continually observed. The galvanometer reading <u>immediately before</u> the discharge commences is taken. This gives the required potential (V_s).

The reason for this procedure is clear. When the glow begins, both the capacity and resistance of the discharge-tube change, so that the circuit is thrown out of tune. At high pressures, where the discharge which takes place at V_s is bright and carries a large current, the detuning of the circuit may be considerable. Immediately the discharge begins the reading of the thermocouple galvanometer decreases abruptly, sometimes to as little as $\frac{1}{2}V_s$.

At this point a very important property of the discharge which has a direct bearing on the measurements of V_s may be described and discussed. If a discharge with internal ~~internal~~ electrodes is initiated at the relatively high gas pressure of 1 mm. it begins usually as (1) a symmetrical glow, both electrodes exhibiting the usual cathodic phenomena, and the middle of the tube containing a typical anode glow with symmetrical striations. If the potential across the tube is now decreased slowly, this régime changes abruptly to another, where (2) the striated column is longer and the cathode glows become convex towards each electrode. As the potential is still further reduced, this again changes abruptly (3) to a faint egg-shaped luminescence near the centre of the tube. Further reduction of potential causes the discharge to disappear. Thus at high pressures there are three typical régimes, and the discharge begins with (1). At lower pressures the discharge begins at V_s with (2), but can be made to exhibit (1) by increasing the potential. At still lower pressures the discharge begins at V_s with (3) and usually can be made to exhibit (1) by <u>greatly</u> increasing the power. Régime (2) is in abeyance at the lowest pressures.

These observations are of the first importance in the interpretation of curves connecting V_s with the gas pressure at constant frequency. According to the theory of Chapter V, the gas may be ionized in several ways - the distance traversed by the electron in acquiring the ionizing velocity determining the type of ionization. It is probable that the three discharges described above correspond roughly to the three modes of ionization, and the fact that the change from the one to the other is not continuous lends colour to this interpretation. The important conclusion, so far as experimental work is concerned, is that the potential V_s is a measure of different phenomena at different pressures. It can only be said to represent <u>one</u> phenomenon over the pressure range where the type of discharge obtained by its application does not alter. This <u>may</u> account for the rather peculiar shape of the experimental curves at low frequencies. Incidentally it may be noted that at really high frequencies there is only <u>one</u> discharge régime.

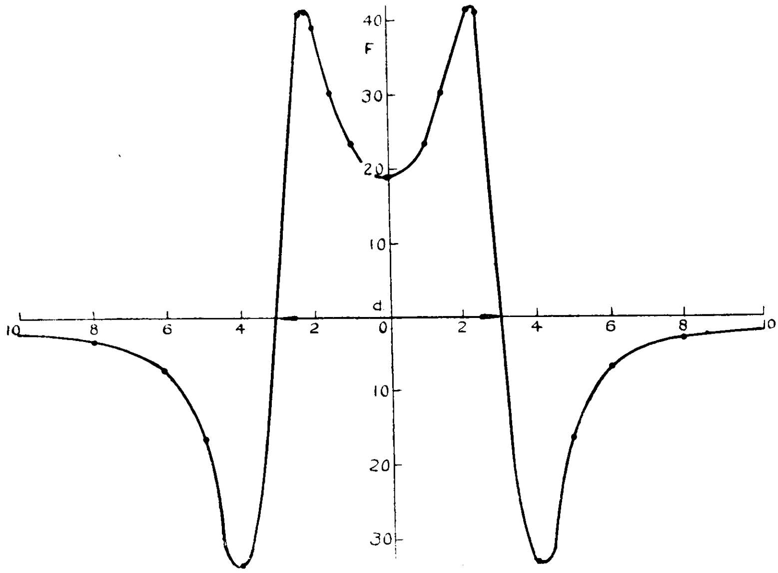
<u>The Measurement of the Potential Difference Necessary to Maintain a Discharge</u>:- As has already been mentioned, the initiation of a discharge detunes the circuit producing the potential difference, owing to the abrupt change in the capacity and resistance of the tube. Hence, when measurements of what will be called the "maintenance potential" (V_M) are required, it is necessary to start the discharge and then tune. Even this procedure is not above criticism, for, as the potential difference across the tube is decreased, the capacity and resistance again change. It may be argued in fact that, as the discharge will probably be carrying a very small current at the extinction voltage V_m, its capacity and resistance will be more nearly those of the dischargeless tube than those of the tube with a heavy discharge

running. In some cases this is true, but in general the writer has found that it is better to tune the circuit with a glow in operation. The exact procedure obviously depends upon the nature of the volt-ampere characteristic of the discharge - a relation which has not yet been established, and about which nothing is known. A general rule is, of course, to observe carefully the detuning which occurs when the glow is started and extinguished, and to adapt the technique accordingly.

The difficulty of the three régimes which has been mentioned in connection with the measurement of V_S does not occur in the measurement of V_M. This causes the curves connecting V_M with gas pressure and oscillation frequency to be much more uniform and to appear simpler. Evidence of this will be given later.

Tubes and Electrodes:- The novelty of producing a discharge with external electrodes has led many workers to attempt quantitative investigations with this arrangement, and the most common type of external electrode is a metal cylinder round the tube. In the opinion of the writer such an arrangement is of little value, for it is difficult, if not impossible, to calculate the electrostatic field in the gas between the cylinders. Even for the theoretical case of infinitely thin ring electrodes, the field between them is very un-uniform. Fig. 33 shows diagrammatically the calculated axial field, where the distance between the rings is 6 cm. and their diameters are 4 cm. The ordinate represents the electric field strength F, and the abscissa the distance along the tube, the electrodes being placed symmetrically with respect to the origin.

Fig. 33.



It will be observed that F varies very considerably with the distance from an electrode, so that any calculation based upon a measurement of $V = \int F\,dx$ is almost impossible. Moreover, the value of F at points off the axis of the tube is given by a pair of elliptic integrals. These too vary between wide limits, becoming very large in the vicinity of the rings.

Other experimenters, notably Gutton and his collaborators, have used parallel plate electrodes external to the ends of a cylindrical tube. In this case, before a discharge takes place, the field in the gas is fairly uniform, and can indeed be made as uniform as necessary simply by increasing the area of the external plates. The objection to this arrangement - an objection which holds for all external electrodes - is that after a discharge has passed in the tube, the end walls have acquired a negative charge. Owing to the greater mobility of the electrons, and the symmetry of the electric field, the glass near the electrodes becomes charged to such a negative potential that the same number of electrons and positive ions arrive at it per second. Hence any calculation of the field in the gas is ridiculously complicated by this unknown charge on the walls. The principal effects of the charge will be first to cause the electrons to move towards the curved surfaces of the tube, and secondly, when these too become negatively charged, to reduce the effective field due to the applied high-frequency E.M.F. Hence, in the opinion of the writer this technique is also of little value.

For a quantitative investigation of the fields necessary to produce discharges at high frequencies, the principal aim of the experimenter must be to eliminate all complicating phenomena. Hence the electrodes should be large parallel plates contained in a very much larger spherical bulb, so that (1) the field in the gas between the plates may be calculated, and (2) wall effects are eliminated.

Unfortunately, in order to test the writer's theory, it is necessary to have as large a distance between the electrodes as possible - something of the order of 20 cm., and few glass-blowers care to blow a bulb of very much greater diameter. Hence the writer had to be content with a tube of the following dimensions.

Length = 30 cm.

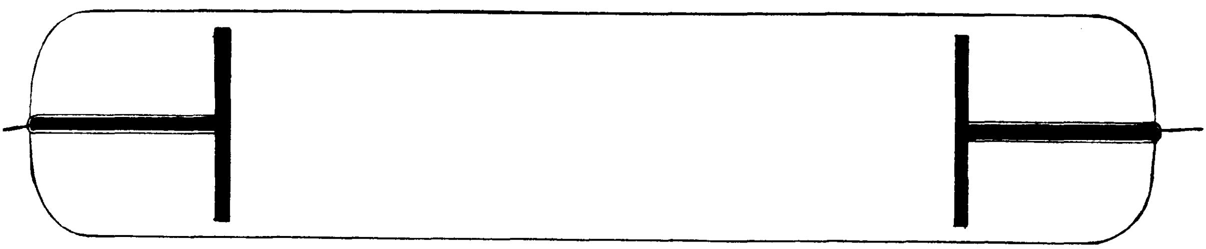
Diameter = 6 cm.

Diameter of plate electrodes = 5 cm.

Distance between electrodes = 20 cm.

Fig. 34 is a sketch drawn to scale. The electrodes were of aluminium in one case and of steel in another.

Fig. 34.



As Dr. James Taylor has wisely remarked, à propos of his own painstaking researches on sparking potentials, "All discharge-tube work suffers from grave disabilities". Chief among these disabilities are the difficulties associated with the final purification of the filling gas and the electrodes, and these are common to both high-frequency and direct-current work. In the experiments to be described in Part II all the usual precautions were taken to ensure that only pure dry gas found its way to the discharge-tube. Liquid air traps were used to eliminate mercury vapour, and the electrodes were brought to an equilibrium state by a long series of discharges, before any measurements were taken.

Vacuum Apparatus:- A word will suffice to describe the vacuum system. A three-stage mercury diffusion pump backed by a

Hyvac oil pump gave a vacuum better than 10^{-5} mm. of mercury when desired. The pressure was measured by two gauges. One was a simple McLeod gauge reading down to 0·1 mm. of mercury with an accuracy of 5%. The other, a Gaede shortened McLeod gauge, measured pressures from 0·1 mm. to 0·0001 mm. and detected a pressure of 0·00001 mm. All joints were glass-sealed and numerous traps were inserted at suitable points for use with liquid air. The gas was fed into the apparatus from a Hoffmann hydrogen generator through a tube of soda lime, a tube of calcium chloride, a tube of phosphorus pentoxide, and a capillary tube. It was possible to adjust the gas leak and rate of pumping to maintain a flow of gas through the discharge tube at any pressure between 3 and 0·0001 mm.

PART II.

Results.

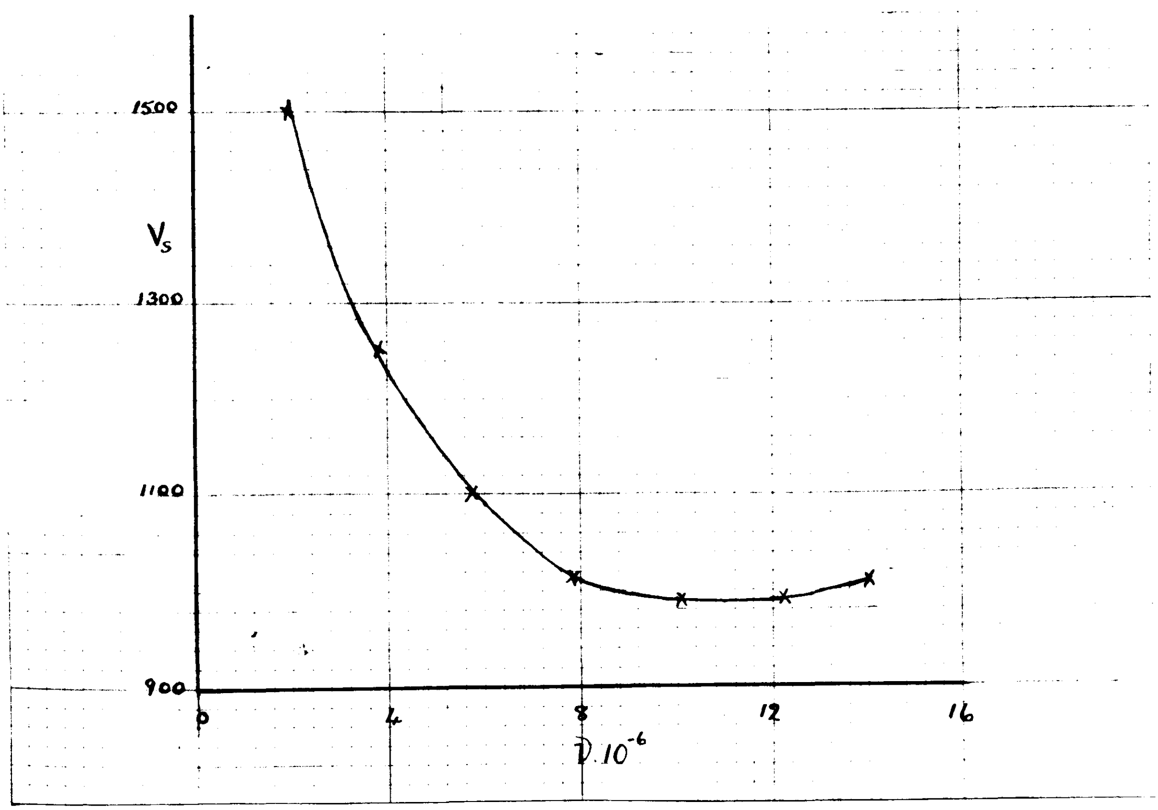
1). Variation of V_s with the Frequency:- The experiments performed by other investigators and the results of which have been quoted in the previous chapter indicate that for a given discharge tube there exists a critical frequency of the applied potential difference for which the electric field required to produce a glow is a minimum. It has also been shown that for frequencies greater than this critical one the writer's theory of the discharge probably holds, while for lower frequencies it requires modification to take account of the abnormal fields at the electrodes. The first experiments performed were therefore designed to find the critical frequency for the tube used. The mode of procedure was as follows:-

The gas pressure was adjusted to a comparatively high, constant value, so that the term B/p in the characteristic equation

$$\mathcal{E} = Ap + B/p$$

would be negligible. Then, by the methods described in Part I of this chapter readings were taken of V_s for various values of the frequency ν between 10^6 and $1{\cdot}5.10^7$. The results are shown in Fig. 35, where ν is the abscissa and V_s the ordinate. V_s is expressed for obvious reasons as the peak potential. The gas pressure in this case was 1·05 mm. of mercury.

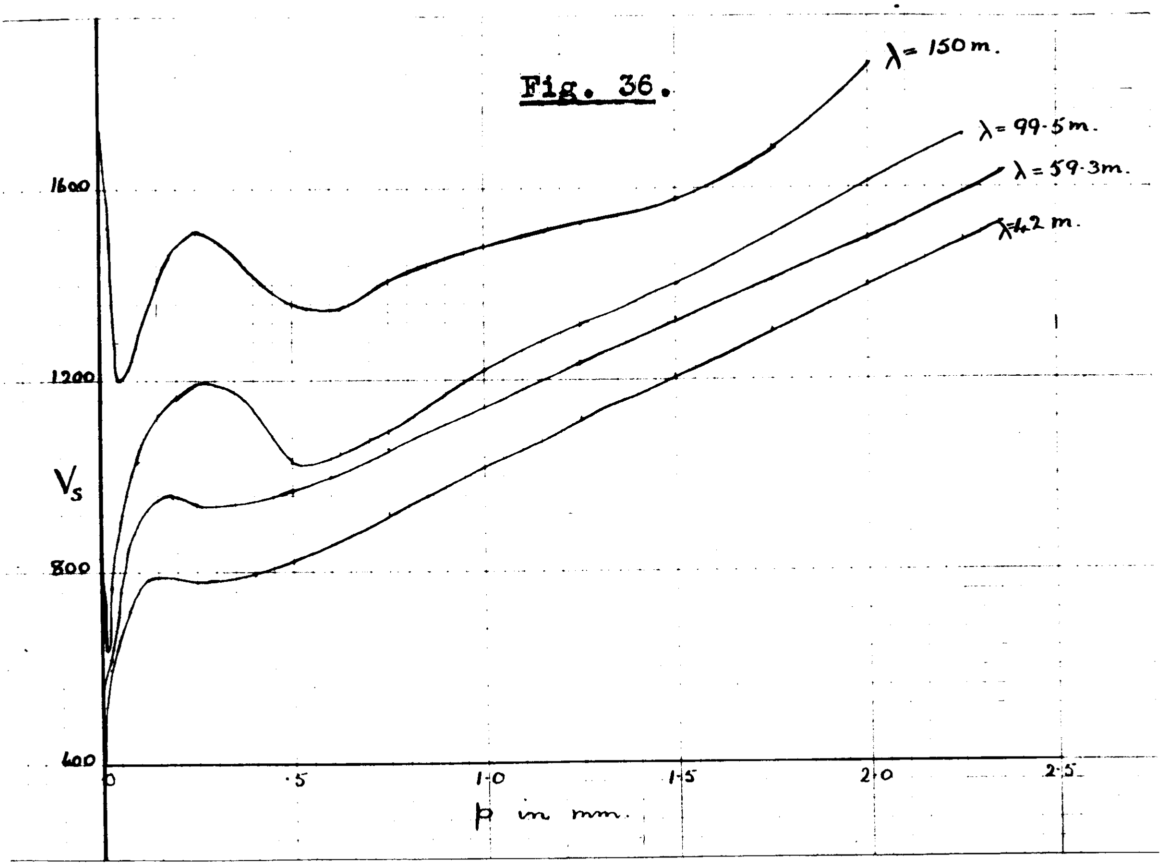
Fig. 35.



V_s is difficult to measure. It is only by allowing some minutes to elapse after the glow has been suppressed before taking the next reading that consistent readings can be obtained. The reason for this will be explained later. The curve of Fig. 35 is an average one drawn from many observations at the same pressure. It shows quite definitely that the critical frequency for the tube in question (that described in Part I and illustrated in Fig. 34) is between 10^7 and $1{\cdot}2.10^7$; let us say at $1{\cdot}1.10^7$, or at wavelength 27·2 metres.

2). Variation of V_s with the Gas Pressure:- Still using the oscillator of Fig. 30, series of readings of the mode of variation of the starting potential with the gas pressure were taken at various frequencies. In the first instance these observations were taken in the following manner:- Hydrogen was admitted to the tube to a pressure of about 3 mm. of mercury. Then the maximum potential difference obtainable was applied across the tube at a known frequency, and the gas pressure was slowly reduced until a discharge just started. Then in the usual manner readings were taken at various lower pressures of V_s and p . In these first experiments no liquid air was used either in the neighbourhood of the discharge tube or the pressure gauges. Hence the readings were stopped at $p = 0{\cdot}01$ mm., since below this the partial pressure of the mercury vapour was not negligible. The observations are only of qualitative value, since even a trace of mercury vapour may cause a considerable change in V_s. Fig. 36 is a typical set of results. The abscissa measures the pressure in mm. of mercury, the ordinate V_s in peak volts. The wavelengths of the oscillations are also noted.

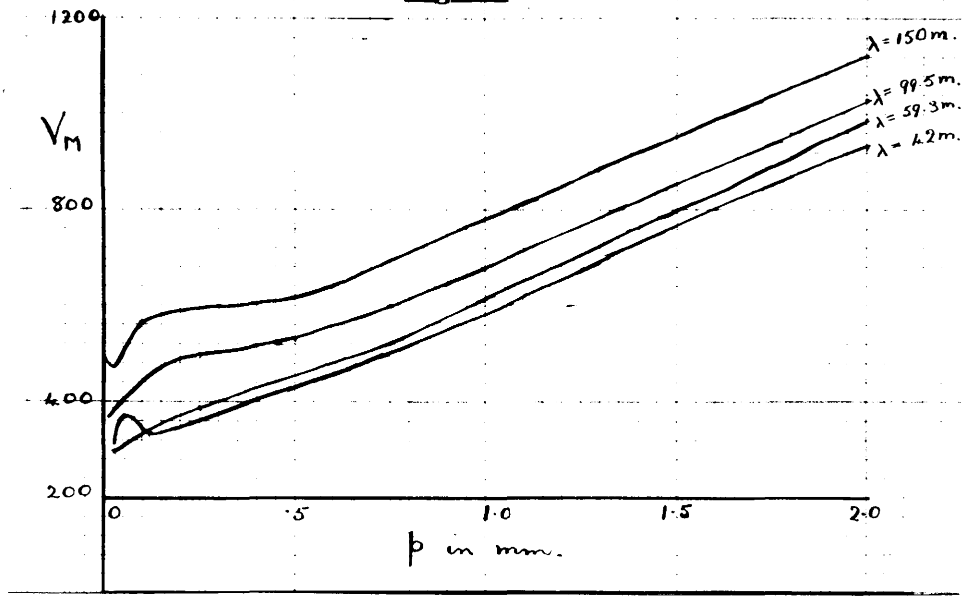
Fig. 36.



3). <u>Variation of V_M with the Gas Pressure</u>:- The corresponding curves for the maintenance potential across the discharge (measured by the methods previously described) are shown in Fig. 37. These were taken at the same time as the curves of Fig. 36. It will be observed that V_M in all cases is considerably lower than the corresponding V_s. Again the results are of qualitative value only.

The sets of results given in the previous paragraphs (2) and (3) were taken merely as general verification of the work of other observers, and as a test of the apparatus. The results which are about to be detailed are quite new, and, naturally, of considerably greater interest.

Fig. 37



4). <u>The Current-Voltage Characteristic of the High-Frequency Discharge</u>:- The experiments which have just been described suggested to the writer that it is very difficult to say what is actually measured by V_S or V_M without some knowledge of the current-voltage characteristic of the discharge. As has already been mentioned, it is difficult to measure V_S accurately; indeed Kirchner [26], Brasfield [33] and others have stated that they found it impossible to obtain consistent results for the starting potential, and have instead measured V_M , or, alternatively, the potential difference required to produce a given current through the tube.

The writer has no doubt that this difficulty is traceable to the shape of the volt-ampere characteristic of the discharge, and arises from the processes now to be considered.

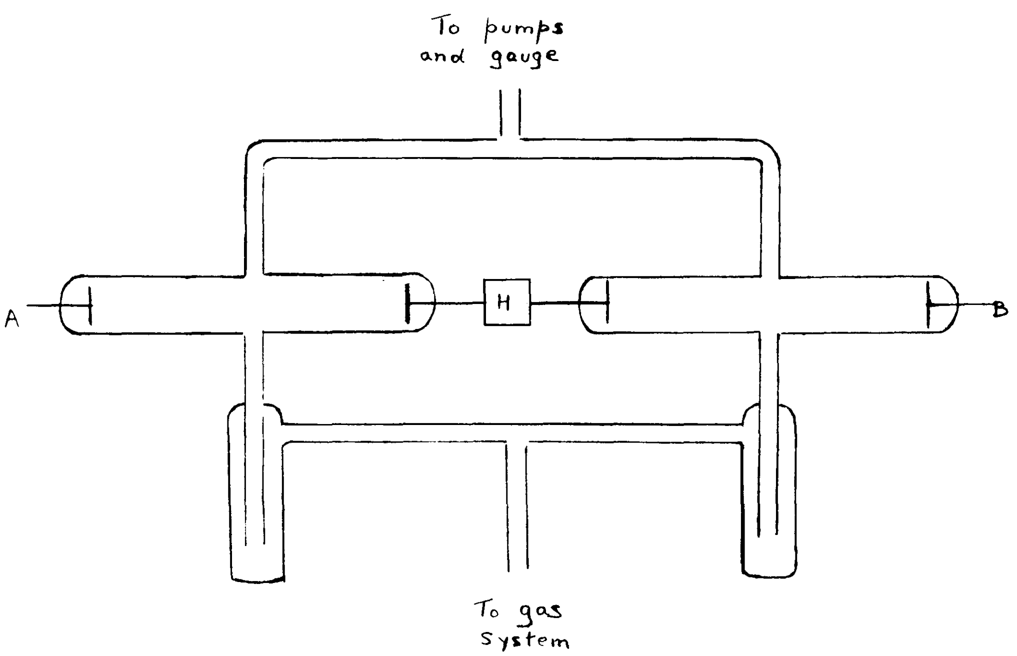
In order that any discharge may begin there must be at least one electron in the gas, and under these circumstances some potential difference can always be found at which ionization will occur. But, as has been shown by Taylor[9], Penning[9] and others (see Fig. 7 (p.30) of Chapter II), the starting potential is actually a function of the number of electrons present in the gap, where, of course, that number is reasonably large. In the direct-current discharge (for which this has been demonstrated) it is almost impossible to arrange matters so that a large number of ions are present in the gas between two electrodes before a discharge begins, for, as may readily be imagined, the constant unidirectional electric field sweeps the ions out of the gap almost as fast as they are generated. Hence, unless a very special technique is employed, no matter how soon after the suppression of a direct-current glow we again increase the voltage to its sparking value, the ions which were present have almost entirely disappeared, and the discharge does not begin until the static sparking potential V_s (Fig. 7) has been reached.

With a high-frequency field the matter is entirely different. In this case after a discharge has been suppressed, the ions may remain in the gas for many seconds, and, owing to the oscillatory nature of the electric field, many may escape neutralisation at an electrode. Hence, on increasing the voltage again there is what may be termed a potential source of current present, and, if the high-frequency discharge characteristic is similar in shape to the direct-current characteristic, the discharge will start at a voltage lower than the static sparking potential V_s.

This gives a very satisfactory explanation of the difficulty encountered in measuring V_s. The writer has actually been able to start the discharge at a voltage only slightly higher than V_M by rapidly increasing the potential across the tube immediately after the extinction of the previous glow.

The attempt was then made to measure the current-voltage characteristic directly. Two discharge tubes, each exactly similar to the one already described, were joined in series, as shown in Fig. 38.

Fig. 38.



The high-frequency potential was applied across AB and a heater and thermocouple for measuring the high-frequency current were placed between the tubes at H. It was hoped by this means to measure the conduction current through the tube as a function of the potential difference across it. It was necessary to have two tubes so that the heater and thermocouple might be at a potential node.

The arrangement worked well for comparatively large conduction currents (of the order of 10 milliamp.), but at the frequency used ($1\cdot5.10^7$) the capacity current through H was of the same order. Hence it was impossible to investigate the really important part of the characteristic, where the currents are small. In the range over which reliable readings could be obtained (5-20 milliamp.) it was found that the current increased linearly with the applied voltage; this corresponds to the similar part of the direct-current glow characteristic.

Fortunately, further evidence with regard to the mode of variation of the current with the voltage for small currents was indirectly obtained. The experiment is interesting.

As has been mentioned, the mode of controlling the potential across the tube was by means of the valve filament current. This actually controls the power output of the oscillator and therefore indirectly the power available in the discharge tube circuit (see Fig. 32). Now the potential across C′ for a given value of the filament current depends upon the current flowing in the discharge tube - ~~the~~

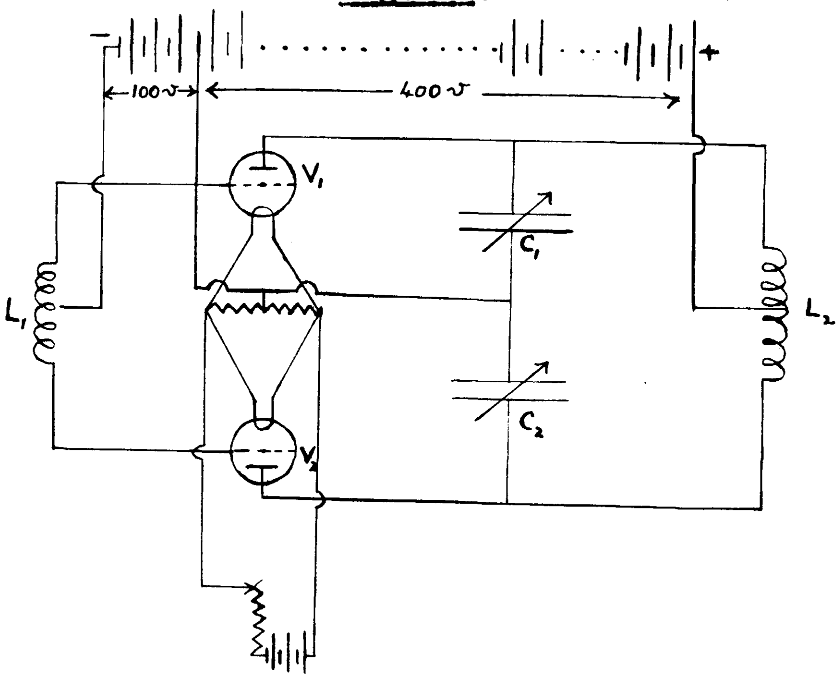
the greater the load on the circuit, the smaller the voltage across C'. The glow was started and the filament current slowly reduced, readings being taken of the potential across C' in the usual way. When the glow was very weak, it was observed that decreasing the filament current actually increased the potential across C', and this continued until the discharge went out altogether. The immediate inference is that for small currents through the discharge a decrease in energy input causes a decrease in the conduction current through the tube and an increase in the voltage across the tube. Hence the small current part of the volt-ampere characteristic must be negative, as it is in the case of the direct-current glow.

The general conclusion is that for high-frequency as for direct-current discharges the volt-ampere characteristic is of the general form of Fig. 7. The writer is of the opinion that it will be exceedingly difficult to verify at the frequencies used by direct experiment that this conclusion is correct.

5). <u>The Final Experiment</u>:- Utilizing all the information which he had already obtained with regard to the high-frequency glow, the writer finally attempted the critical experiment of measuring carefully the absolute values of V_S for a very high frequency at various gas pressures. For this purpose a new oscillator was constructed.

<u>The Oscillator</u>:- This is of the "push-pull" type. The circuit is shown in Fig. 39. The valves V_1 and V_2 were Marconi LS6A, dissipating about 25 watts each. The oscillating circuit

Fig. 39.



consists of the coil L_2 with the series condensers C_1 and C_2; the grid circuit to the frequency of which the anode circuit must be tuned consists of the coil L_1 and the capacities formed by the grid-filament spacing of the valves. L_1 and L_2 were centre-tapped. To vary the frequency of the circuit it was necessary to change the coil L_1 and tune the condensers C_1 and C_2. This oscillator is remarkably efficient at high frequencies. It has been used by the writer at $\nu = 6.10^7$. In this case coil L_2 consisted of a single turn of wire of radius 3 cm. and the coil L_1 about 4 turns of the same dimension. The circuit was constructed from a design published by the Research Department of the General Radio Co. of America.

Owing to the remarkable electrical symmetry of the oscillatory circuit, it was found to be possible to connect the discharge tube (and potential measuring condensers and thermocouple) directly across the coil L_2. This increased the efficiency of the arrangement.

Readings were then taken by the usual method of the peak potential across L_2 required just to start a discharge. Minutes were allowed to elapse between each reading to ensure that the number of electrons still in the gas was small. Liquid air was employed at the following points in the system:-

1. Between the pump and the discharge tube.
2. Near the McLeod gauges.
3. Round a trap immediately below the discharge tube.

By these means a very consistent set of readings was obtained at gas pressures between 1·5 and 0·01 mm. of mercury. The frequency of the applied potential difference was $1{\cdot}215.10^7$. The curve in Fig. 40 shows the results.

This curve can be represented throughout its entire range with a very high degree of accuracy by the equation

$$V_s = 4230p + 6{\cdot}35/p$$

which is of the form of the "characteristic equation". Moreover, if the electric field in the discharge tube (E) is assumed to be V_s/d, where d is the distance between the electrodes, then

$$E = V_s/d = V_s/21{\cdot}3 = 199p + 0{\cdot}298/p$$

or

$$E \doteqdot 200p + 3/10p.$$

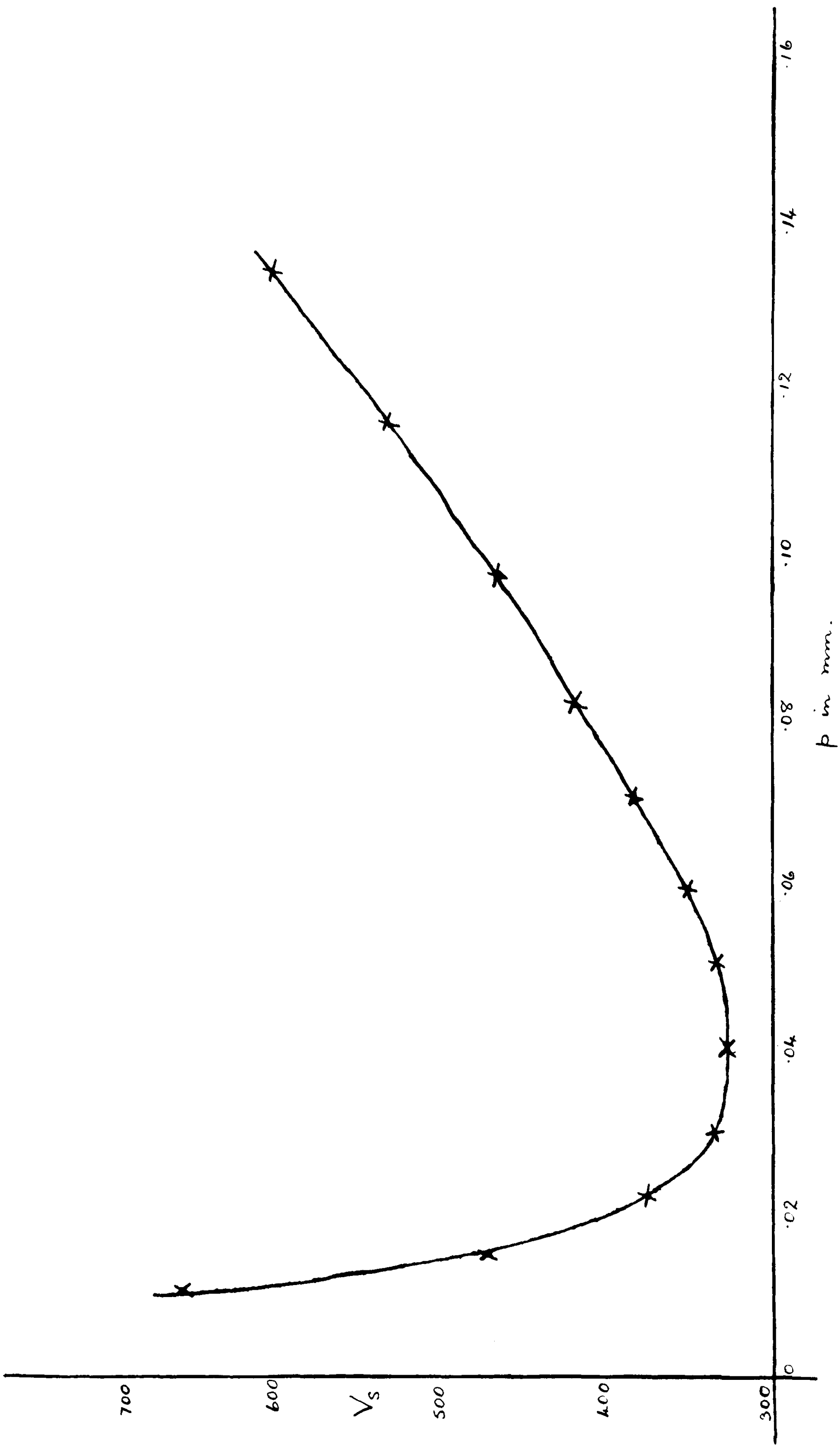
To test the absolute validity of the writer's theory, write

$$200 = V/10^8 K \qquad \text{and} \qquad 3/10 = 2\pi^2\nu^2 K/10^8 \tfrac{e}{m}$$

Substituting $\nu = 1{\cdot}215.10^7$ and $\frac{e}{m} = 1{\cdot}77.10^7$,

$$K = 0{\cdot}221 \qquad \text{and } V = 44{\cdot}2 \text{ volts.}$$

Fig. 40.



The value of K found from the Kinetic Theory of Gases is 0·121, while the ionization potential of hydrogen is about 16 volts. Hence K and V are of the correct order, and may indeed be theoretically correct.

This very stringent test of the theory therefore yields eminently satisfactory results.

CHAPTER VII.

A NEW THERMIONIC VOLTMETER.

Introduction.

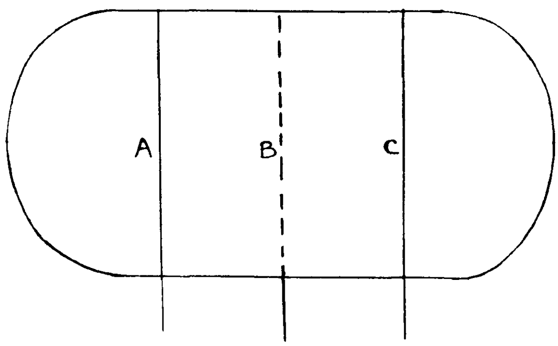
In his search for a simple and accurate means of measuring high potentials at high frequencies the writer has tried many devices some of which are described in Chapter VI. Out of the multiplicity of arrangements with which experiments were made, one piece of apparatus of more than experimental interest has emerged. This is in essence a thermionic voltmeter in which the critical potential is defined by means of secondary emission. The instrument is capable of measuring alternating potential differences of the order of 1000 R.M.S. volts at frequencies of the order of 10^7/sec. with an accuracy which depends only upon the D.C. instruments used (a galvanometer and voltmeter). The writer had no difficulty in obtaining an accuracy of 2%. The thermionic voltmeter has an effective capacity of less than $0{\cdot}07\mu\mu F$ which is comparable with the normal leads to a condenser, while the power absorbed by it is a very slowly varying function of the applied voltage and need never be more than 4 milliwatts.

Resonance Electronic Oscillations.

It may be well to sketch briefly the theoretical analysis which suggested the instrument. Although this theory has not been applied experimentally, it is possible that it may yet lead to a new means of obtaining oscillations of very high frequency.

Consider the hypothetical three-electrode tube represented diagrammatically in Fig. 41.

Fig. 41.



A and C are metal discs, coated, let us say, with an alkali metal, so that they are photo-electrically active when exposed to visible radiations. B is a wide-meshed gauze placed symmetrically with respect to A and C. Let $AB = BC = d$.

Suppose now that by some means the electrodes A and C are maintained at $-V\cos\omega t$ and $+V\cos\omega t$ respectively, and that the gauze B is maintained at the constant potential V_o.

Then if at $t=0$ an electron starts from electrode A ($x_1 = 0$) with zero velocity ($\dot{x}_1 = 0$), it moves under the action of the field

$$\frac{V_o + V\cos\omega t}{d}$$

Therefore
$$m\ddot{x}_1 = \frac{V_o + V\cos\omega t}{d}\,e$$

Hence
$$\dot{x}_1 = \frac{1}{d}\frac{e}{m}\left[V_o t + \frac{V}{\omega}\sin\omega t\right]$$

And
$$x_1 = \frac{1}{d}\frac{e}{m}\left[\frac{1}{2}V_o t^2 + \frac{V}{\omega^2}\left(1 - \cos\omega t\right)\right]$$

Let $x_1 = d$ when $t = \frac{\pi}{2\omega}$.

Then
$$\omega^2 d^2 = \frac{e}{m}\left[V + \frac{\pi^2}{8}V_o\right] \qquad \cdots\cdots (1)$$

Carrying out a similar analysis for the motion of the same electron between B and C, assuming it to have passed through the gauze, then

$$m\ddot{x}_2 = -\frac{V_0 - V\cos\omega t}{d}e$$

and

$$\dot{x}_2 = \frac{1}{d}\frac{e}{m}\left[V_0\left(\frac{\pi}{\omega} - t\right) + \frac{V}{\omega}\sin\omega t\right]$$

if

$$\dot{x}_2 = \frac{1}{d\omega}\frac{e}{m}\left(V + \frac{\pi}{2}V_0\right) \quad \text{when} \quad t = \frac{\pi}{2\omega}$$

and

$$x_2 = \frac{1}{d}\frac{e}{m}\left[V_0 t\left(\frac{\pi}{\omega} - \frac{1}{2}t\right) - \frac{V}{\omega^2}\cos\omega t - \frac{3\pi^2 V_0}{8\omega^2}\right]$$

$x_2 = d$ when $t = \frac{\pi}{\omega}$, if

$$\omega^2 d^2 = \frac{e}{m}\left[V + \frac{\pi^2}{8}V_0\right]$$

which is condition (1).

Also, when $t = \frac{\pi}{\omega}$, $\dot{x}_2 = 0$.

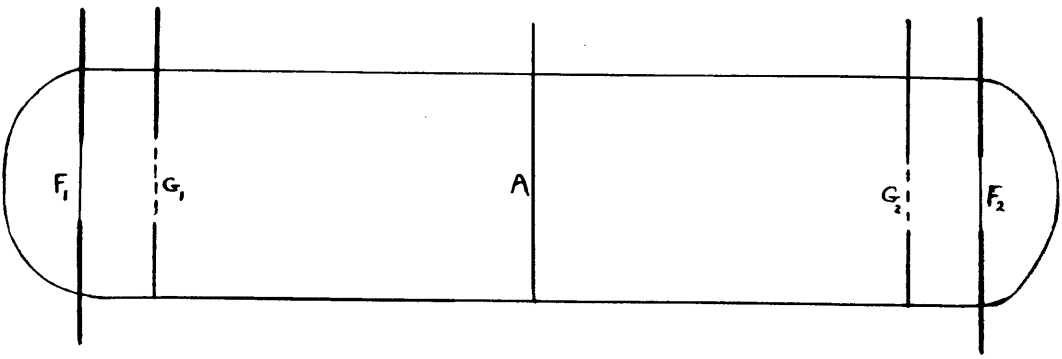
Therefore the three-electrode tube shown in Fig. 41 is in a condition to resonate if condition (1) holds. Suppose, for example, that $\omega = 10^7$/sec., $V = 100$ volts, $d = 5$ cm., then for resonance $V_0 \doteq -80$ volts. Electrons would be emitted by A or C so long as their potentials were more negative than $V_0 + h\nu$ - approximately V_0. Hence electrons would be emitted at each electrode only for a very small fraction of the period of oscillation, and the assumption that the electrons are emitted when $t = 0$ is approximately satisfied.

It was from the above analysis that the writer began his experiments, but the first tube exhibited quite different effects, and in the investigation of these effects the thermionic voltmeter was discovered.

The Thermionic Tube.

The tube finally used was cylindrical in shape, about 14 cm. long and about 3 cm. in diameter. It is shown diagrammatically in Fig. 42.

Fig. 42.



Near each end there was sealed in a short piece of fine platinum wire, the sealing-in wires being of thick platinum. These fine wires F_1 and F_2 acted as filaments at which thermionic emission took place. Exactly mid-way between them a metal disc A was placed. This disc which was of approximately the same diameter as the tube will be referred to as the anode. The sealed-in lead was also of platinum. Then on each side of, and at equal distances from A, two other discs G_1 and G_2 were placed. These were pierced near their centres by a number of 1 - 2 mm. holes, so that electrons accelerated from F_1 and F_2 could pass through to A. The discs G_1 and G_2 will be called the grids. The distances between the electrodes were as follows:-

$$F_1G_1 = F_2G_2 = 1 \text{ cm.}, \quad G_1A = G_2A = 5 \text{ cm.}$$

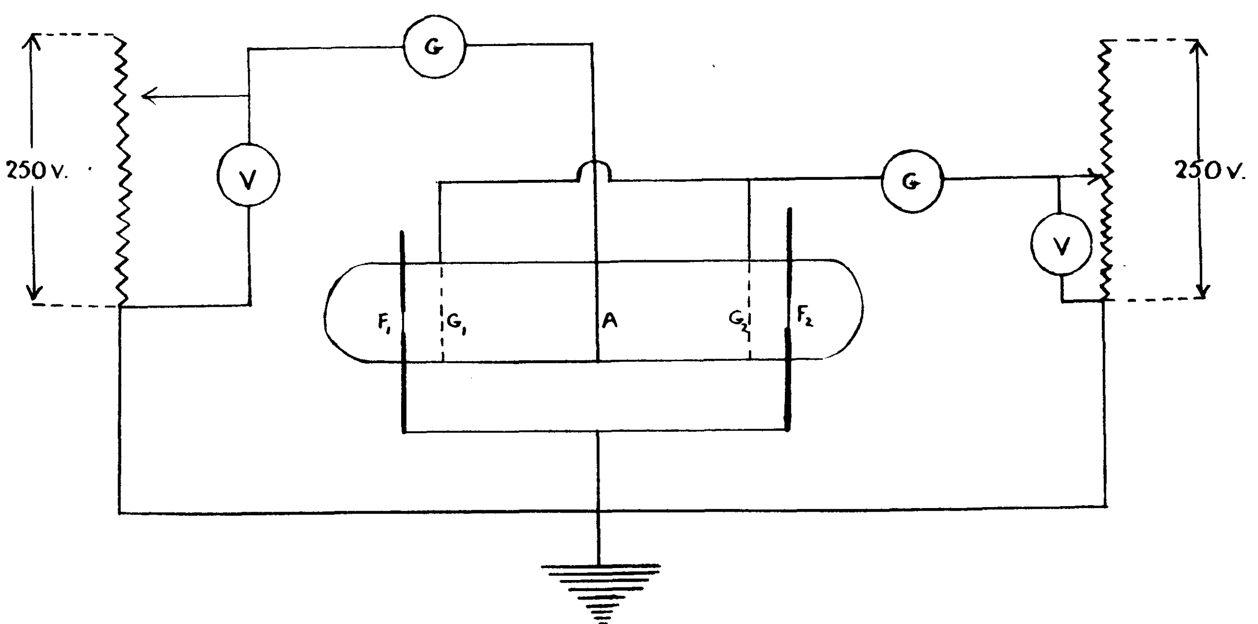
A careful glass-blower can adjust these distances to within 1 mm.

In the experiments to be described, the tube was kept permanently on a vacuum system, the pumps used being a three-stage mercury diffusion backed by a Hyvac. Liquid air was used round a trap in the vicinity of the tube, when it was thought necessary. There is, of course, no reason why such a tube should not be baked-out, sealed off and mounted suitably, if it is to be permanently used.

Static Characteristics.

The filament current was accurately and easily controlled by a sensitive rheostat, and measured with an accuracy of ½%. About 0·45 amperes through each filament was sufficient to give a copious saturation current. The characteristics were measured by means of the circuit shown in Fig. 43 , the filament battery connections being omitted for the sake of simplicity.

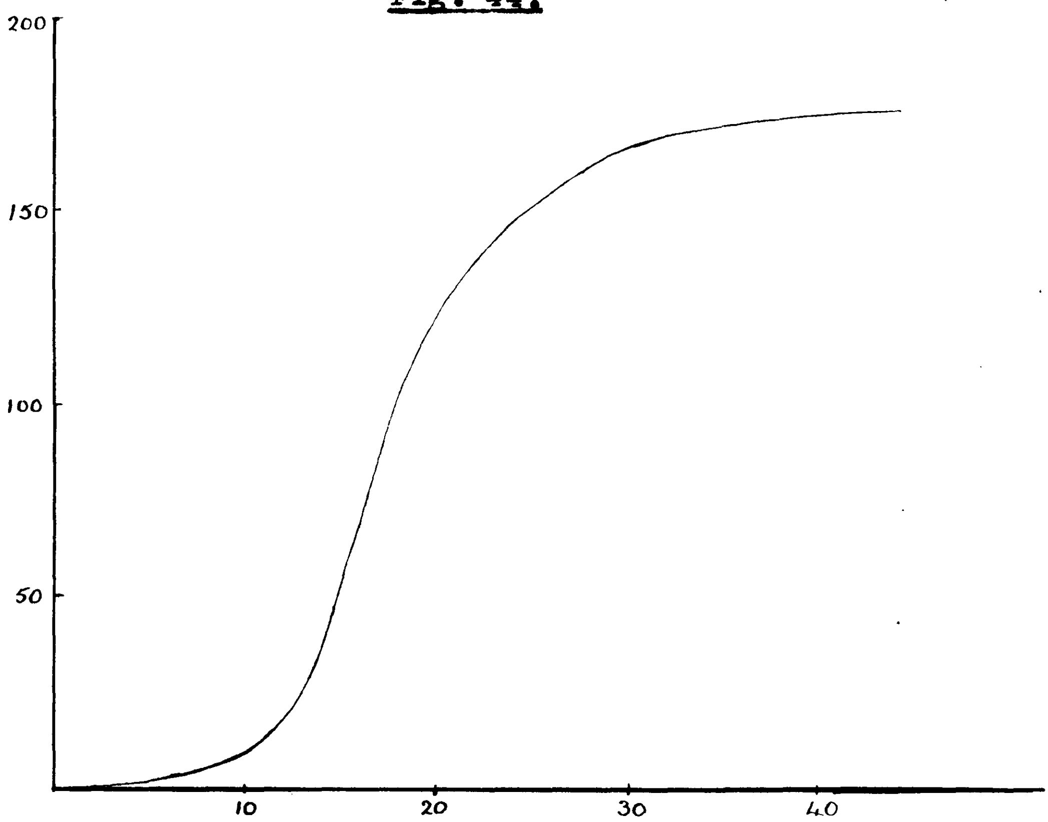
Fig. 43.



The filaments were both approximately at earth potential. The grids were connected together and a common lead taken through a galvanometer to a potentiometer, so that any potential up to +250 volts could be applied. This potential (V_G) was measured by the voltmeter, and the grid current (i_G) by the galvanometer. An exactly similar circuit was employed for the measurement of the anode potential (V_A) and the anode current (i_A).

I. The most important characteristic is that exhibiting the variation of i_G with V_G, V_A being maintained at a constant value, and the simpler part of this characteristic is for values of V_G between 0 and 40 volts with $V_A = 0$. Fig. 44 shows this simple characteristic.

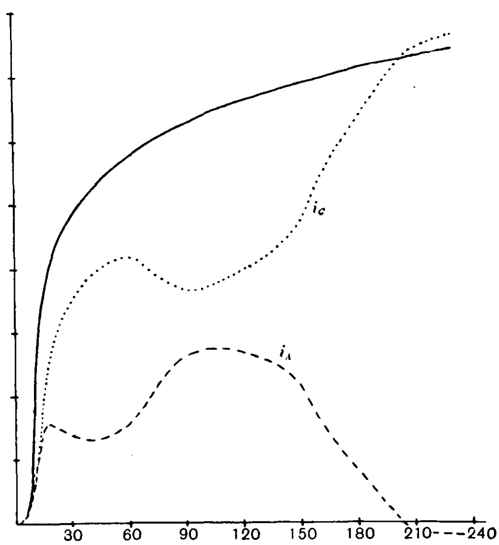
Fig. 44.



This is the normal thermionic valve curve, showing that the grid current becomes approximately saturated (for $V_A = 0$) at $V_G = 30$ volts.

The interesting feature of the valve appears when similar characteristics are drawn for V_A equal to some large positive value, and when the curves are continued to much higher values of V_G. In Fig. 45 the dotted line . . . . . exhibits the variation of i_G with V_G, V_A being maintained at +180 volts. The dashes - - - - - show the simultaneous variation of i_A with V_G, and the whole line is obtained by adding i_A and i_G.

Fig. 45.



The fact that the lumped current (full line) approximately saturates at $V_G = 30$ volts, and that it does not exhibit any traces of "kinks" due to ionization of the residual gas, indicate clearly that the characteristics are due to thermionic current only. There are no spurious effects. The figure is reminiscent of the typical tetrode valve characteristic. The maxima and corresponding minima on the two i_A, i_G curves are due to the emission of secondary electrons, and a general explanation of the shapes of the curves may be given in the following terms:-

When $V_G = 0$, both i_A and i_G are zero, showing that the grids act effectively in electrostatically screening the filaments from the anode. As V_G becomes positive but less than 17 volts, some electrons are accelerated towards the grids and approximately one-half of these find their way to the anode. Those which reach the anode without interference will possess the full energy of 180 electron-volts, and such fast electrons will certainly produce "secondaries" on impact with the anode surface. But the electric field between the anode and grids is such that the majority of these secondaries return to the anode.

As V_G is further increased from 17 to about 40 volts, the field between the anode and grids becomes proportionately weaker, and the secondaries with maximum energy begin to find their way to the grids despite the opposing field. Hence i_A decreases and i_G increases more rapidly. This is the explanation of the first maximum on the i_A curve. When V_G reaches 40 volts, the current i_A begins again to increase. The reason is to be found from a consideration of the relative potentials of the filaments, grids and anode. If the grids were not there, the potential at the planes which they occupy would be approximately $V_A.FG/FA = V_A.1/5 = 36$ volts. Hence, as V_G is gradually increased from 30 to 40 volts, at some intermediate potential there will be no transverse field in the neighbourhood of the grids. Therefore more electrons will be shot through to the anode, the anode current will increase and the grid current will tend to decrease. This is the explanation of the first minimum in the i_A curve and the first maximum on the i_G curve.

About this point, too, the electrons striking the grids begin to produce measurable quantities of secondaries, some of which move towards the anode. This also partially accounts for the decrease in i_G. From this point onwards, as V_G is increased, no new processes come into play, but more and more electrons and secondaries are absorbed by the grids. Hence i_G begins again to increase, and continues to increase, while i_A again decreases to zero. Ultimately i_A becomes negative, representing a current of electrons from the anode. This shows that with potentials of the order of 200 volts applied to the grids each electron which is shot through to the anode produces (on the average) more than one secondary, and that all these secondaries are collected by the grids.- hence the positive anode current.*

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*It is interesting to compare these curves with that shown in Fig. 20, Chapter IV. The processes at work are the same in the two cases.

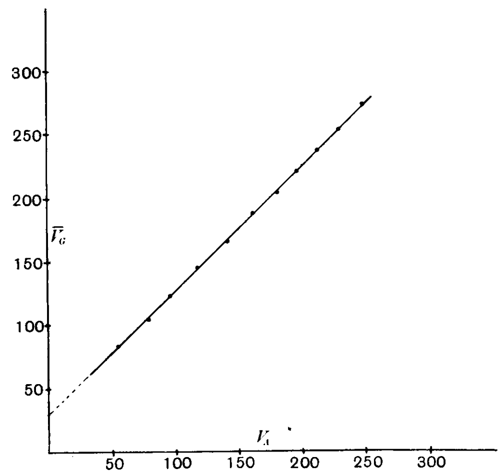
So far as the action of the tube as a voltmeter is concerned, the interesting feature of Fig. 45 is the fact that i_A becomes zero when V_G is about 30 volts greater than V_A. Let the potential of G at which the anode current becomes zero be denoted by $\overline{V}_G$. If V_G is greater than $\overline{V}_G$, the current i_A is in one direction; if V_G is less than $\overline{V}_G$, the current i_A is in the other direction. Moreover, the gradient of the V_G, i_A curve is steep where i_A is zero, so that $\overline{V}_G$ can be determined very accurately.

II. The second characteristic, shown in Fig. 46, exhibits the mode of variation of $\overline{V}_G$ with V_A. This was obtained by adjusting V_A so that no current flowed to or from A, and the accuracy of the adjustment depended solely upon the sensitivity of the galvanometer used. The writer employed a Gambrell instrument with a sensitivity of 600 mm. per micro-ampere on a scale at 1 m. A less sensitive galvanometer might have been used, if the filament current had been increased to give a correspondingly greater thermionic emission, for it was found that this characteristic is quite independent of the electron current through the tube. The figure shows clearly that the relation between $\overline{V}_G$ and V_A is linear. For the tubes used by the writer the relation was

$$\overline{V}_G = 0\cdot98\ V_A + 30,$$

measured in volts over the range $V_A = 60$ to $V_A = 400$. These experiments were repeated with another tube similar

Fig. 46.

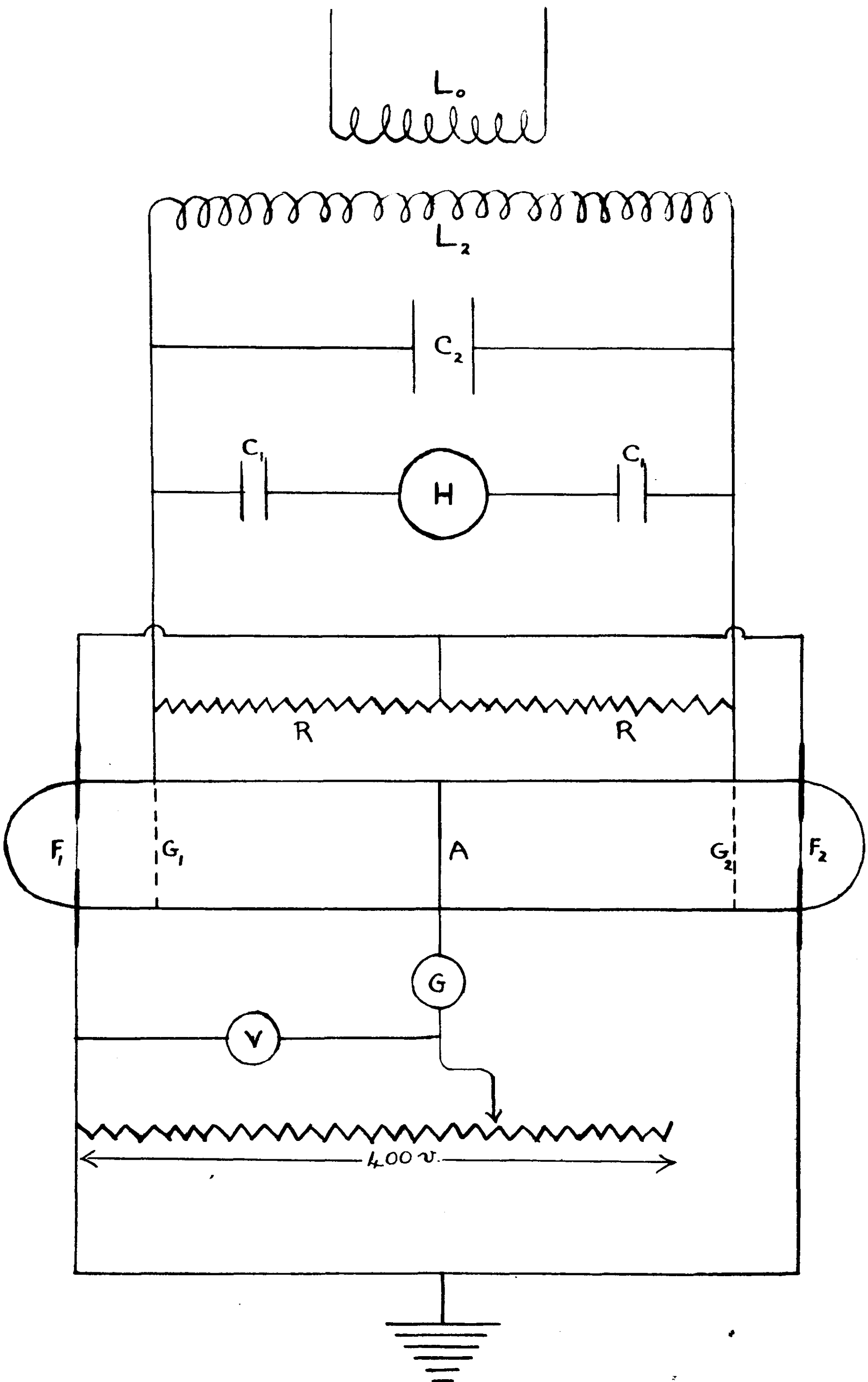


to that already described. The electrode distances were as before, but the grids and anode in this case consisted of circular pieces of wire gauze. It was difficult to distinguish between the $\overline{V}_G$, V_A characteristics of the two valves. The gradient in the two cases was the same; any dissimilarity was in the intercepts on the $\overline{V}_G$ axis. It is therefore suggested that the gradient of the line shown in Fig. 46 is a function only of the ratio of the electrode distances, FG/GA, a fact which, as will be seen later, is of considerable importance.

The Thermionic Voltmeter.

From a consideration of the results of the experiments already described, the writer decided that it should be possible to measure an alternating potential applied across the grids $G_1 G_2$ in terms of a steady potential V_A applied to A, by adjusting the value of V_A to obtain no anode current. To test this the circuit shown in Fig. 47 was arranged.

Fig. 47.



The inductance L_0 in the oscillatory circuit of a powerful valve oscillator was loosely coupled to a larger inductance L_2. In parallel with this inductance was the variable capacity C_2 (parallel plates - air dielectric). Across the capacity were shunted the two equal small fixed condensers C_1 (parallel plates - air dielectric) and mid-way between these was the vacuum heater and thermocouple (Standard Cables Ltd.). Also in parallel with C_2 were the two equal resistances R (100,000 ohms) of very small capacity, the mid-point being taken to earth. The grids of the valve G_1 and G_2 were connected as shown.

The circuit was geometrically and electrically symmetrical, so that the following arrangements were secured:

(1) The potential at G_1 was $-V$ when the potential at G_2 was $+V$.

(2) The capacity to earth of the heater and thermojunction did not invalidate the readings at high frequencies, since they were at the earth potential node of the circuit.

The arrangements for measuring the potential of A were as before, except that higher potentials could be used. The oscillator was efficient over the range of wave-length 300-30 m., the wave-length being measured with an accuracy of 1% on a standard wave-meter. The coupled coil L_2 was changed as the wave-length of the oscillations decreased, to keep the capacity C_2 large compared with C_1. The high frequency alternating potential applied to the grids of the valve was measured by the current through the heater as detected by the thermocouple. The instrument was carefully calibrated in the usual manner.

With this circuit readings were taken of the mode of variation of V_A with the R.M.S. potential across $G_1 G_2$ for no anode current. It was found that, using the same galvanometer, it was possible to adjust V_A with an accuracy of 1 volt, and that the settings could be repeated with the same accuracy at any subsequent time. Hence the results shown in Fig.48 were obtained. These are typical of the particular valve used by the writer, and are quite independent of the filament current. The ordinate measures the R.M.S. potential (V_R) across $G_1 G_2$ in volts, as calculated from the readings of the thermocouple and heater. The principal deductions which may be made from the graphs can be stated as follows:

(1) There is a linear relation between V_R and V_A.

(2) The gradient of the line $V_R = AV_A + B$ is not a function of the frequency of V_R.

(3) The intercept on the V_R axis (B) is a linear function of the frequency.

Summing these conclusions in the form of an equation,

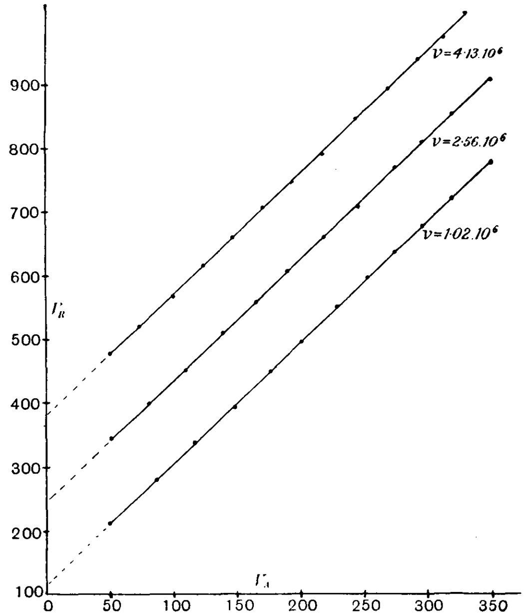
$$V_R = AV_A + B(\nu + C) . . . .(1)$$

where A, B, C are constants for a given tube and are independent of the filament current, and ν is the frequency.

The results enumerated were tested as far as possible. It is not suggested, of course, that the linear equation (1) holds for all values of V_A. The range of the writer's experiments are indicated in the figure by the full lines, and for that range the calibration equation deduced for the valve was

$$V_R = 1{\cdot}88V_A + 8{\cdot}60.10^{-5}(\nu + 3{\cdot}5.10^{5}).$$

Fig. 48.



The explanation of the form of equation (1) may now be given. When the frequency is small, the time taken by the electrons to move from the filaments to the anode will be negligible compared with an oscillation period of the applied potential. Hence, some of the electrons will arrive at A with velocities corresponding to $\frac{1}{2}V_P$, where V_P is the peak potential across $G_1 G_2$. Therefore, when $\nu \rightarrow 0$, we might expect V_A to be related to V_P by the equation found for the static characteristic (2), i.e.,

$$\tfrac{1}{2}V_P = 0\cdot98V_A + 30.$$

If the frequency is large, then the time taken by an electron to traverse the distance between the anode and the filaments will be comparable with the period of oscillation, and no electrons will arrive at A with velocities corresponding to $\frac{1}{2}V_P$. Therefore the corresponding value of V_A will be smaller than at low frequencies, and a term in some power of ν must be added.

Similarly, even at low frequencies, if the wave-form of the oscillation is such that the peak factor is large, then no electrons will reach A with velocities corresponding to $\frac{1}{2}V_P$, and conversely a flattening of the potential waves, even at high frequencies, will increase the maximum electronic velocities. This shows that consistent results can only be obtained if the wave-form of the applied oscillation is constant, although the error due to inconstancy will be relatively smaller at low frequencies. The writer tested this explanation by deliberately distorting the potential wave (by increasing the coupling between L_0 and L_2). The calibration curves of the valve were then found to be different from the normal by as much as 10% in a single reading for a given frequency. Hence, it may be suggested that the valve might be adapted for the stabilization of wave-form.

In the opinion of the writer the thermionic voltmeter described compares very favourably with other methods of measuring high potentials at high frequencies. It is true that the instrument is not an absolute one, as is the heater and thermocouple arrangement. In view of the fact, however, that the writer was able to reproduce his results with a constancy of 2% over many weeks of experimenting, and that the new instrument may therefore be calibrated once and for all, an equation being constructed for use with it, it might be said to be as absolute as an ammeter or voltmeter usually is. No doubt the effective range of the instrument could be altered by an alteration in the ratio of the electrode distances, while its absolute sensitivity depends largely upon its absolute inter-electrode distances. It should therefore be possible to construct a similar tube to perform any desired measurement at any frequency. As has already been mentioned, the exceedingly small capacity of the tube and the small fraction of the power which it absorbs make it an ideal instrument for use at very high frequencies.

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