"THE ULTRA-VIOLET RADIATIONS EMITTED BY POINT DISCHARGES."

THESIS

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Introduction.

It was in February 1926 that C.E.Wynn-Williams* published the results of the first systematic investigation of the phenomenon termed the "three-point effect". This phenomenon was described by him as follows. "A spark gap is connected to an induction coil or other impulsive high potential apparatus. Corresponding to any given set of conditions, there will be a certain maximum length of gap, depending on the peak voltage of the coil, the dimensions of the electrodes etc., for which a spark can pass regularly. If the gap is made of slightly greater length than this, the other conditions remaining the same, the spark will not pass. If, however, a third pointed electrode is brought near one of the main electrodes, it is found that, under certain conditions, the spark will again pass regularly in the main gap." Put in the most general terms the effect is that a sharp metallic point facilitates the passage of a spark across a gap near which it is placed.

The explanation given by Wynn-Williams of the phenomenon is summarized at the end of his communication as follows. "It is therefore inferred that the three-point effect is caused by the ionization of the gas in the main gap by a radiation, believed to be a form of entladungstrahlen, emitted by the pilot discharge."

The investigation to be described in the present thesis was initiated for the purpose of studying further the source and properties of the radiation referred to; it has, however, also led the writer to a rather different explanation of the action of the charged metallic

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*Phil. Mag. vol.i. p.353 (1926).

point. Consequently the work can conveniently be divided into two sections; the first is concerned with the explanation of the effect, and with some allied questions regarding the mechanism of the spark discharge. The second section describes the investigation of the nature of the radiations themselves.

Since the radiations are capable of ionizing air, they must lie on the X-ray side of the Schumann region of the ultra-violet. Wynn-Williams suggested that their mean wave-length lay between 13Å. and 1000Å. This fact precludes the possibility of spectroscopic invest--igation for two reasons. First, the radiations are totally absorbed by about three centimetres of air at atmospheric pressure, and are not transmitted by any non-gaseous substance except celluloid films thin enough to give interference fringes with reflected light. Secondly, the radiations are not regularly reflected by a mirror surface, and consequently could not be investigated by the usual grating.

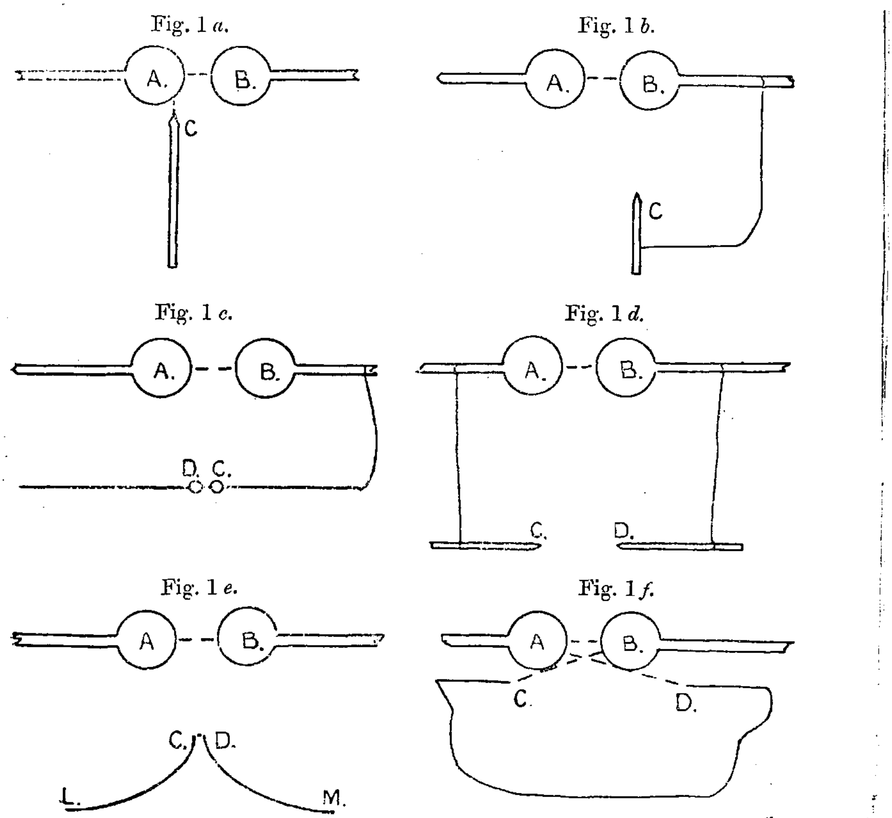
Throughout the experiments to be described, therefore, the radiations were detected and ultimately their intensities were measured by electrical means, advantage being taken of their ionizing and photo-electric effects.

CHAPTER 1.

The Influence of Charged Metallic Points on the Spark Discharge.

Experimental Arrangements.

In the first figure are shown the principal arrangements of the spark-gap and metallic point which were used in the experiments. The arrangement known as the "three-point gap" is shown in Fig.1a, where A,B are the main spark-gap electrodes and C is an insulated metal rod the point of which is placed very near one of the main electrodes. This is the arrangement which is used commercially in magneto gaps, and the effect is only produced when small sparks pass between C and the main electrode adjacent to it. The rod C need not be pointed; a blunt end is almost equally effective.



Figs.1b and 1c show arrangements which were also used by Wynn--Williams in his investigations. The rod C in Fig.1b is connected to one of the main electrodes, and under these conditions need not be very near the gap AB. The end of C, however, must be very sharply pointed, and the radiation is believed to originate in the silent discharge at this sharp point. In Fig.1c the pointed third electrode is replaced by a small metal sphere held near another small sphere D attached to the end of an insulated wire. Owing to the electrical capacity of the wire and the sphere D, a small spark passes between the latter and the sphere C. This spark was found by Wynn-Williams to be the source of ionizing radiations similar in their properties to those proceeding from the silent discharge from C in Fig.1b.

The Spark-gaps Employed in the Present Experiments.

The writer has found that, in addition to the arrangements of gap and auxiliary conductors described in the previous section, there are a number of other systems in which similar effects are produced. Some of these are shown in Fig.1. Fig.1d shows a symmetrical arrangement in which two sharp needles C,D, are connected to the main electrodes. If the distance between the points C and D is just great enough to prevent a spark from passing between them, the effect on the main gap is very marked if the distance between AB and CD is not more than 10 cm. (AB was 1cm.). This is the arrangement which was used most extensively in the experiments to be described.
Another symmetrical arrangement is shown in Fig.1e, in which a very small spark passing between C and D, the adjacent ends of insulated wires, takes the place of the silent discharge. This arrangement is also very effective up to a distance of 4 cm. between AB and CD.

If the ends L,M are joined byx a copper wire, the effect is still found if the small auxiliary gap CD is within 1 cm. of A or B. In Fig.1f C and D are the points of two needles the outer ends of which are connected by a copper wire, but which are otherwise insulated. In this arrangement the effect on the main gap is very marked, even though no sparks pass between A and C or between B and D.

The Source of the Radiations.

With the arrangement of Fig.1d a series of experiments was made with the object of determining the exact source of the radiations. The source of potential was a large induction coil (10 in. spark) used in conjunction with a motor mercury-jet interrupter. Such a system ensured that the peak potential across the coil remained very constant, when the primary current was constant, and thus caused the sparking to be very regular in any gaps which were em--ployed. The potential applied to the main gap being adjusted so that sparks just failed to appear, a thin plate of paraffin wax having a narrow aperture was placed between AB and CD, and moved about until the effect on the passage of the spark was greatest. In this way it was found that practically the whole of the effect originated in the immediate neighbourhood of one or other of the points C,D.

The effect was most marked when the aperture allowed a straight path in air from the positive point to the point A on the negative electrode(Fig.2). This result was confirmed by attaching a narrow tube of the same material to the wax plate, as shown in Fig.2, in order to limit the radiation to a still narrower pencil. The most favourable position of the shield is shown in the Figure. With this arrangement the greatest distance, AC, at which the effect could be produced was 8 cm., the width of the main gap, AB, being as usual 1 cm. If the shield was so placed that the pencil failed to strike either of the main electrodes, but passed directly between them, the effect on the main gap was much weaker, being only observable when the distance AC was not more than 4 cm.

In another experiment one of the main electrodes, A, was covered with a thin layer of paraffin wax except at the point nearest the other electrode. The auxiliary gap CD was then moved to one side, as shown in Fig.3, so that no radiation could pass directly from C or D on to the uncovered part of A. With this system the effect on the main gap was much more marked when B and D were negative than when they were positive.

Fig. 2.

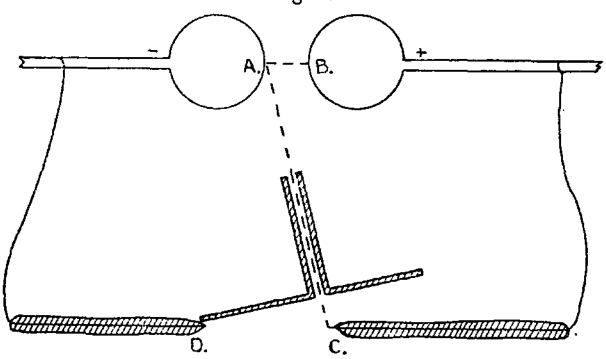
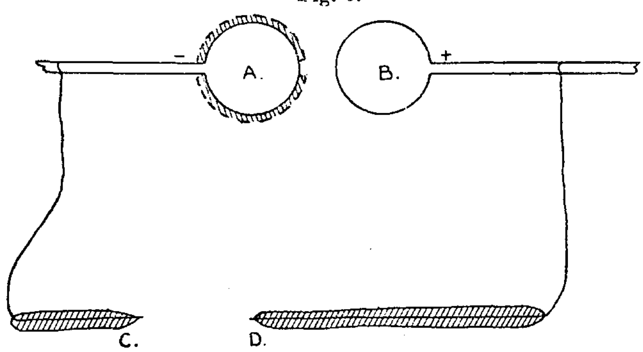


Fig. 3.



Practically identical results were obtained when the aperture in the wax shield was covered with a thin film of celluloid. This indicates that the effect on the main gap is caused by electro--magnetic radiation, since it is highly improbable that positive or negative ions can penetrate such a film under the conditions of the present experiments. Such penetration would be likely to occur only if the charged particles were <u>projected</u> with high velocity from the points, but in other experiments strong evidence was found (as will be seen later) against this supposition.

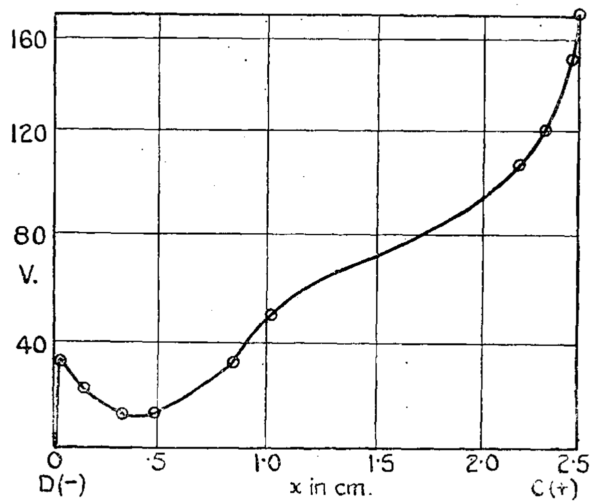
On the whole this series of experiments strongly suggests that, while a small effect arises from a radiation which ionizes the air in the main gap, a much greater part of the effect is photo--electric in character, arising probably from ultra-violet radia--tion proceeding from the neighbourhood of the positive point. This conclusion seems to be borne out by the fact that the effect of the metallic point in facilitating the discharge at the main gap is very much less marked if the electrodes of the latter are dirty or oxidized. It may be remarked that results practically identical with those just described were found when either of the main spark electrodes ~~were~~ was earthed.

With the arrangement of Fig.2, in which a very narrow directing tube was attached to the wax shield, a series of observations was made with the object of determining more exactly the source or sources of the radiation. First the tube was placed so as to be in line with the point A and various points in the line CD, thus examining the relative intensities of the photo-electric radiation from different parts of the discharge. The radiation was found to be much more intense at the positive than at the negative point, while an important conclusion was that, in order to obtain the effect to a marked degree, it is not necessary that C or D should be in line with the point A. The air near C or D is almost equally effective, and an appreciable effect is produced by points in the air at 2 mm. from C or D. Similar experiments in which the main electrodes were shielded allowed the source of the ionizing radia- -tion to be investigated. The effect due to ionization appears to be of almost equal intensity whether it proceeds from the neigh- -bourhood of the positive or negative point. As before, the air near the point seems to be the source of the radiation.

For comparison with these results a series of measurements was made of the potential in various points in the auxiliary gap CD. For this purpose a water-dropping collector, consisting of a fine glass capillary tube, was placed just above the line CD, so that water fed into it broke into drops in this line. The water was connected to one terminal of a Kelvin vertical voltmeter, the other terminal of the instrument being connected to D. The reading on the voltmeter indicated the R.M.S. voltage between D and the collector. The results of these experiments are shown in Fig.4, the ordinate representing the R.M.S. potential difference between D and the various points of the gap CD. The derivative curve, representing the potential gradient along CD, is shown in Fig.5.

The electric force is greatest near the negative point D (cathode fall), and, on the assumption that the radiations are generated by the impact of ions on air molecules, it is to be expected, according to the quantum theory, that the radiation of greatest frequency will be generated near D. If V is the fall of potential in a very short distance (comparable with the mean free path of the electron in air at atmospheric pressure), the frequency is

Fig. 4.



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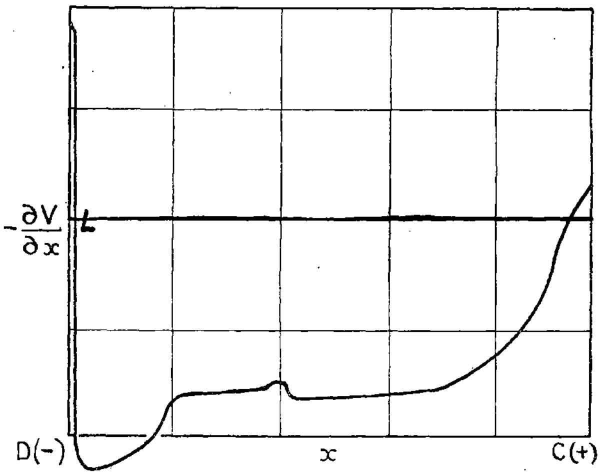


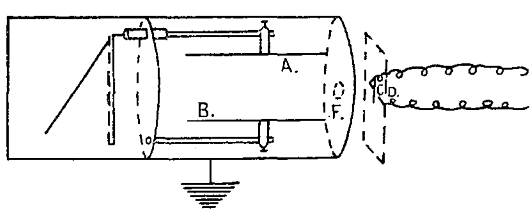
given by the quantum relation $h\nu = Ve$. Although the immediate vicinity of the point D may give rise to radiation of greater frequency than that from the neighbourhood of C, a greater volume of gas near C may give rise to some radiation, owing to the more gradual rise in the electric field. That is, if the field necessary to produce radiation of frequency $\bar{\nu}$ is represented by the ordinate DL in Fig.5, then within a very short distance from D there will be a high probability of radiation of that frequency. But although the field near C is never so high, its strength is greater than DL over a larger distance. Consequently the quanta of radiation of frequency $\bar{\nu}$ emanating from the vicinity of C will be as numerous, if not more numerous, than those emanating from D.

It seems probable therefore that the radiation which produces the effect on the main gap is not the radiation of greatest frequency.

Experiments with an Ionization Chamber.

In order to obtain further information as to the properties of the radiations, the main gap AB was removed and replaced by an ionization chamber containing two parallel metal plates, A, B, one of which, A, was insulated and connected to an ordinary gold-leaf electroscope. The other plate, B, was at first connected to the wall of the chamber. The arrangement is shown in Fig.6. The point gap, CD, connected to the induction coil, was placed horizontally in front of the chamber and 2 cm. from it, and by means of the slotted shield the radiation from C or D could be allowed to enter the chamber through the aperture F. C was the positive and D the negative point. The upper plate and consequently the electroscope, were charged to about +600 or -600 volts, and the rate of discharge was observed with C or D opposite the slot. The numbers given in the table below indicate the angular movement of the gold leaf in a fixed time (about 10 seconds), and are assumed to be proportional

Fig. 6.



to the currents flowing to or from A. The normal leakage of the electroscope in 10 seconds was quite negligible. The rate of discharge of the electroscope was comparable with the normal leak when points between C and D were opposite the slot.

Potential of A.	Point Source.	Current to A.
+600	C	7
-600	C	120
+600	D	550
-600	D	10

These results clearly indicate that the current to the plate A is not due to ionization of the air between A and B alone, since in that case the first two results in the table would be equal and also the last two. To investigate this further, a Wilson tilted electroscope was substituted for the ordinary electroscope and the following series of experiments was carried out:- The earthed plate B of the ionization chamber was replaced by a similar insulated plate which could be charged to any desired potential, while the plate A was connected to the leaf of the tilted elect--roscope. The aperture F was covered with gauze connected to the earthed walls of the chamber in order to eliminate inductive effects on A due to the charges at the point gap. The electroscope was found to be sufficiently sensitive with the attracting plate charged to a potential (with respect to the earth) of ± 210 volts, the leaf system and plate A to ± 25 volts, and the instrument tilted to about 30°. The case of the electroscope was of course earthed, and the point gap with shield was arranged as in the former ex--periment.

(a) The plate A was charged to + 25 volts, the electrode D (negative) being placed opposite the aperture. Plate B was charged to various potentials V_B. The rate of discharge of the electroscope was found to vary as V_B was varied, and the graph of the results is shown in Fig.7, Curve a. The ordinate represents the rate of discharge of A, the abscissa the potential V_B.

(b) In the next experiment the plate A was charged to − 25 volts, and electrode C (positive) was placed opposite the aperture. The relation between the rate of discharge of A and V_B is shown in Fig.7, Curve b.

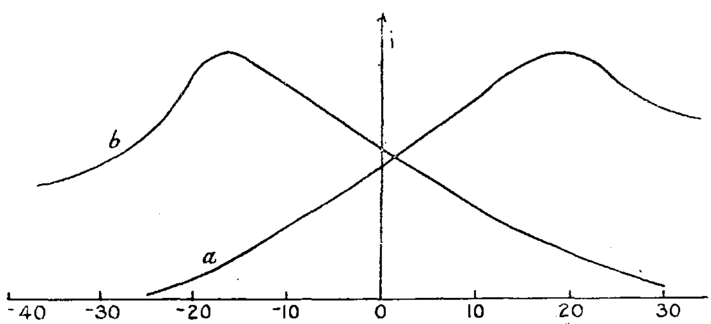
In order to interpret these results it may be supposed that there are three conceivable ways in which the point C or D might cause discharge of the electrode A, viz.;-

(i) By the emission of an electromagnetic radiation which ionizes the air between A and B.

(ii) By the emission of ions of the same sign as the point, pro-jected with a comparatively large velocity through the air between A and B.

(iii) By the production of ions in the vicinity of the aperture F, but not in the space between the plates A and B.

Fig. 7.



(i) According to the first hypothesis, the current from A to B should clearly be zero when A and B are at the same potential, and as the difference between V_A and V_B increases, the current should steadily increase, i.e. the current varies with $\pm(V_A - V_B)$.
(ii) In this case also the current would be due to the electric field between A and B. If the projected ions did not ionize the air through which they passed, then the current would increase as the negative potential of B increased. If the projected ions ionized the air, then this case would reduce to (i), and the current would vary as in that case.
(iii) On the third hypothesis the current to A would depend entire--ly on the electric field between the edge of the electrode A and the earthed gauze over the aperture. A consideration of the distribution of electric charge in the system within the ionization chamber leads to the conclusion that the gauze will have a very small charge when the potentials of the plates A and B are equal but opposite. On the other hand, when A and B are charged to the same potential, the induced charge on the gauze is very much greater. Since tubes of electric force originate in charges on conductors, and since the electric force in the vicinity of a conductor is measured by the number of tubes of force originating on it per unit area, it is concluded that the force between the plate A and the gauze F is very much greater when A and B are at the same potential than when they are at equal and opposite pot--entials. Consequently it is to be expected that a much greater current of ions will move from the gauze to either plate when they are at the same potential than when they are at opposite potentials. Another way of looking at the same problem is to consider extreme

cases of the potential V_B. If V_B is very large and of the opposite sign to V_A, then the potential near the gauze F will be of the same sign as potential V_B. Consequently ions of this sign will be repelled to the gauze, and none will reach the plate A. Now the current measured was the current to A, and this was due to ions of the opposite sign from V_A. Therefore , if V_B is large and of the opposite sign from V_A, no current will be obtained. As the potential of the plate B approaches that of the plate A, there will come a time when a fairly large current of ions will move towards A. Then if V_B is very large and of the same sign as V_A, although ions will be attracted in large numbers from the gauze into the chamber, they will almost all find their way to the plate B, since the field of force between A and B will tend to drive them towards B. Thus, again, when V_B is very large, a very small current will be obtained. This indicates that a maximum current will occur when V_B is somewhere near to V_A.

The curves of Fig.7 obtained experimentally agree very well with this hypothesis, and accordingly it is concluded that the ions produced by the discharge do not reach the air between A and B, unless they are assisted by the action of an electric field. It is thus possible to put a limit to the distance from the discharge at which ions are <u>produced</u>. This limit, as shown by these experi--ments, is about 3 cm.

Similar experiments with A negatively electrified and D opposite the aperture, or with A positively electrified and C opposite, led again to the curves of Fig.7. Since in this case the ions carrying the current were of opposite sign to the point source, the experiment shows that both kinds of ions are produced by the influence of each point.

In order to test the matter further, the following experiment was tried. The earthed wire gauze across the aperture F was replaced by an insulated piece of gauze which could be charged to various potentials. With A at + 25 volts, and B at + 20 volts, it was found that the current to A varied almost directly as the field from the gauze to A, the current increasing as the negative potential of the gauze increased. Similarly, with A charged to − 25 volts and B to − 16 volts, the current from A increased as the positive potential of the gauze increased. No current could be observed in either case if the gauze and A were at the same potential, or if the distance of C or D from the gauze was more than 3 cm. These experiments also support the hypothesis that the ions are produced near the gauze, but not in the space well between the plates A and B.

Another experiment was arranged to determine roughly the relative numbers of ions present at various distances from the source of the radiation. For this purpose a strong electric field was required, and therefore the tilted electroscope was replaced by the upright type, which could be used at potentials of about 600 volts relative to the case, which was earthed. The gauze was removed from the aperture F (Fig.6), and the point gap was arranged so that it could be moved in a direction perpendicular to itself and the face of the ionization chamber. This allowed the distance $\underline{x}$ from F to CD to be varied and to be accurately measured. The experiment consisted in observing the rate of discharge of the electroscope for different values of $\underline{x}$, which was varied from 4 cm. to 6 cm. In all cases the relation between the rate of discharge and x was found to be represented by an exponential expression of the form $i = i_0 e^{-kx}$, where i is the rate of discharge of the elect--roscope and i_0 is some constant.

The exponential decrease in the current must now be explained on the assumption that no ions are produced at distances greater than 3 cm. from the discharge. Since ions did reach the chamber, there must be a field of force between the place where the ions are formed and the aperture F. This is not surprising when the high potential of the plate A is considered. This plate (positive) will attract negative and repel positive ions, so that the current flowing from the vicinity of the discharge to the aperture will consist entirely of negative ions. Let this current at any point be i across unit cross-section, and let the current at the point beyond which no ions are formed (3 cm. from the discharge) be i_0. The decrease in the current must be due to some form of diffusion of the ions. No recombination occurs, since there are assumed to be no positive ions present. This diffusion is principally due to the mutual repulsion of the ions, causing them to move away from one another. Consequently the decrease in the current i will be proportional to the number of ions present, or, if the flow is being considered, will be proportional to the current itself. Thus, if k is the fraction of the current lost along 1 cm. of the distance x, the increase in the current across an element dx will be represented by the quantity $-kidx$. That is

$$di = -ki\,dx,$$

giving

$$i = i_0 e^{-kx}.$$

It is to be noted that this diffusion is not the same as that occurring when ions of one sign are present in a closed chamber.

There the diffusion current is due to the absorption of ions near the surface of the chamber; the expression representing such diffusion is entirely different.

There now remains to be investigated the question of how these ions are produced by the action of the point discharge. The experi--ments made with the spark gap indicate that ionizing radiations emanate from the vicinity of the point. None of the experiments described above have given any evidence to contradict this view. On the other hand they have established that the production of the ions is brought about either by fast moving ions, projected from the points and capable by reason of their velocity of ioniz--ing air, or by an electromagnetic radiation. They have also shown that in either case the ionization ceases at a distance of about 3 cm. from the gap.

Again the tilted electroscope was employed, and the aperture F was screened by an earthed wire gauze. In this experiment, however, the aperture was also covered by a thin film of celluloid similar to that used in the spark-discharge investigations. The electrode B was earthed, and the point gap was about 1 cm. from the aperture F. Observations were taken of the rate of discharge of A. In this case the normal leakage of the electroscope had to be measured and deducted. The readings varied considerably with the intensity of the field across the gap CD, a typical result being given in the following table:-

Potential of A in volts.	Source.	Rate of Discharge of A.
+25	Positive point.	6
+25	Negative point.	4
-25	Positive point.	6
-25	Negative point.	4

In each experiment the ratio of the rates of discharge of plate A due to C and D did not vary when the potential of A was changed from +25 to -25 volts. This means that whatever emanates from the point and penetrates the celluloid produces equal numbers of positive and negative ions. That is, in this case true ionization of the air in the chamber is taking place, either by the action of a radiation or by the impact of high-velocity ions on air molecules. It is highly improbable that anything of the nature of cathode or positive rays is given off by a point discharge in air at atmospheric pressure, and ions of smaller velocity than these would be stopped (or at least lose their ionizing speed) by the impact with the celluloid film. Moreover, the previous experiments have shown that ionization does not take place at distances greater than 3 cm. from the discharge; material particles brought to rest by 3 cm. of air would certainly be unable to penetrate the film. The conclusion is therefore that the ionization is caused by an electro-magnetic radiation.

Another point to be noted is that the experiment did not allow any photo-electric radiation which might be present to be detected, since the electrodes A and B were not "visible" from C or D. The numbers given are therefore measures of the relative intensities of the ionizing radiations from the two points, as detected at 3 cm. from their sources. It cannot be stated, however, that the relative intensities at the sources are in the same ratio, as that assumes that the radiations from the two points are of the same average wave-length or "hardness", and the experiments on the field of force in the point gap indicated that this was extremely improb--able.

The next experiment was intended to detect and measure the photo-electric radiations which were suspected to be present. The plate B was removed and A was replaced by a clean zinc plate Z, facing the aperture F and about 1 mm. from the wire gauze. Thus radiations from the point acting as source actually fell on the zinc plate, whereas in the previous experiments they did not fall on <u>any</u> metal surface inside the chamber. The aperture was again covered by a celluloid film. The usual measurements of the rate of discharge of the plate Z were taken with the positive point C and then with the negative point D as source. The results are shown below.

Potential of Z in volts.	Source.	Rate of Discharge of Z.
+25	Positive point.	6
+25	Negative point.	4.
−25	Positive point.	24
−25	Negative point.	4

The results with Z positive are a repitition of the results in the previous experiment. Since there is no photo-electric effect with Z charged to +25 volts, the numbers represent the relative inten--sities of the ionizing radiations at 1 cm. from their sources, thus confirming the results already obtained. With Z negative, however, the results are different. The rate of discharge with the negative point as source is as before, showing that little or no photo-electric radiation emanates from it; but the rate of dis--charge with the positive point as source is about four times as great as before. This indicates a strong photo-electric effect due to radiations from the neighbourhood of the positive point. It also shows that the ionizing effect of the radiations is much less powerful than the photo-electric effect, confirming the results obtained with the spark discharge. It is possible and in fact probable that some photo-electric radiation emanates from the vic--inity of the negative point. Our experiment merely indicates that its intensity must be less than one-twentieth of the intensity of the similar radiation from the positive point. So far, direct exper--iment has given no indication as to whether the photo-electric effect is produced by the radiations responsible for the ionization effect or by others of different wave-length. The spark-discharge experiments, however, showed that a photo-electric effect could be produced at the gap when the source of the radiations was (under favourable circumstances) 15 cm. distant. The ionizing radiations under no circumstances will penetrate more than 3 cm. of air. Consequently it may be said that whether the ionizing radiations do or do not produce the photo-electric effect, other radiations are present whose absorption by air is smaller and which are photo-electric.

It is well-known that the photo-electric emissivity of a metal is a function of the wave-length of the incident radiation. The max--imum emission is due to radiation of a certain fixed wave-length. It is also known that the wave-length corresponding to the maximum emissivity varies from metal to metal; in general the more electro--positive metals respond to longer wave-lengths, and the more electro-negative to shorter wave-lengths. Consequently the experiment just described cannot be said to give any general information with regard to the intensity of the radiations. The results must be taken to fefer to zinc only or to allied metals.

The experiments show that both ionizing and photo-electric radiations are emitted by a point charged to a high potential. Photo-electricity is in general associated with radiations of longer wave-lengths than those which ionize air, and therefore it is x reasonable to suppose that the radiations from the point are very heterogeneous in character. A rough spectral analysis might be performed by a series of experiments on the velocities of photo-electrons. With the positive point at a fixed distance from the zinc plate a determination might be made of the minimum wave-length of the incident radiations ,by the usual method of measuring the positive potential to which the plate rises. By making similar determinations with different distances between the source and the plate, a curve might be obtained giving the minimum wave-length as a function of this distance. Such a curve would indicate the type of spectrum emanating from the point. It would of course be necessary to see that the ionizing radiations were not allowed to interfere, by using suitable distances (greater than 3 cm.) between the source and the plate, and by using the celluloid screen. The difficulty in the way of such experiments is the small intensity of the radiations.

Theory of the Action of Charged Points.

The results recorded above can now be applied to the explanation of the action of a third point or system of poimts on the spark discharge; but before proceeding to the explanation it may be well to clear away a preliminary difficulty. Throughout the present thesis the action of the third point has been described as a "lowering of the sparking potential". In practice, when an induction coil is the source of potential difference, this is undoubtedly what occurs. But the term "sparking potential" has a technical meaning which is not implied here. The "sparking potential" across a gap is the potential difference at which a spark will pass, when this potential difference is applied gradually, and is continued for an indefinite time. The effect of time lag is thus eliminated, and it is questionable if any external mechanism can cause any lowering of this potential. In the case of an induction coil the peak potential difference is applied for a very short time only, and consequently the "lag" causes an apparent rise in the "sparking potential". The true action of the third point must be described as eliminating this "lag". The preliminary ionization of the gas in the gap takes place more rapidly, and the current rises more quickly to that necessary to produce a spark. "Lowering of the sparking potential" is therefore a vague description of the action of the point. It is merely a convenient expression, and wherever it occurs in the thesis the above reservations must be kept in mind.

The results described above have led the writer to put forward the following hypothesis:-

1. The lowering of the sparking potential is caused in different ways by different arrangements of points, and the effects of different causes may vary considerably in relative importance as the type of discharge is varied.

2. The two main causes are:-

(a) Photo-electric effects due to ultra-violet radiations from small sparks or the air near positive points.

(b) Ions produced by the ionization of the gas by radiations which emanate from the air near positively or negatively charged points.

(a) The photo-electric radiations are more powerful than the ion--izing radiations in any arrangement where there is a positive point at a distance greater than three centimetres from the main gap. At distances greater than three centimetres the ionizing radiations are completely absorbed by the air before they get to the gap, while the photo-electric radiations can, if the main electrodes are of clean zinc, affect the sparking potential when their source is as much as fifteen centimetres away. If the elect--rodes are dirty or oxidized, however, it is difficult with the same length of gap to obtain an effect at more than three centimetres distance. Similarly the substitution of copper for zinc reduces the range of the effect considerably. These results, along with those described earlier in the paper, show that the photo-electric rad--iations are of prime importance.

(b) The ionizing radiations also affect the sparking potential, but the range of their effect is smaller. Also their action appears to be somewhat complicated. When the distance of a charged point from the spark gap is less than three centimetres, the air in the gap is directly ionized. That this is the case is definitely shown by the ionization chamber experiments, and it is well known that a spark appears more readily in any gap after previous ionization of the gas in it. But experiments have shown that the radiations can affect the air in the gap when their source is at greater distances.

Using the auxiliary gap of Fig.1d and shielding both electrodes from photo-electric radiations, under certain conditions a lower--ing of the sparking potential is found with the distance AB to CD equal to four centimetres. The following two experimental facts must therefore be reconciled:

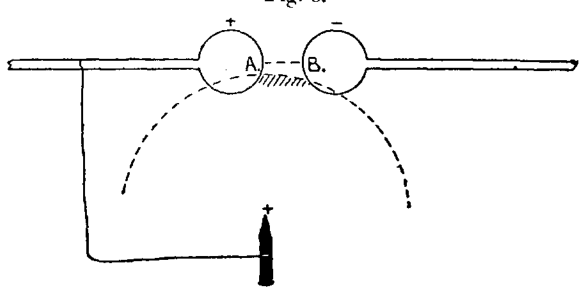
(a) The radiations can affect the spark when their source is four centimetres distant.

(b) The range of the radiations is three centimetres as determined by the tilted electroscope.

The writer has come to the conclusion that the ions produced by the radiations can affect the sparking potential even when they are not in the direct line of the spark, and suggests the follow--ing explanation:-

The ions are produced within the sphere whose central section is indicated by the dotted circle (Fig.8). Ions in the shaded portion of the sphere move under the field of force to one or other of the electrodes, the diffusion being negligible owing to the strength of the field. The energy acquired under the field of force in the last free path of the ion is liberated when it strikes an electrode and this energy takes the form of pulses of electromagnetic

Fig. 8.



radiation which are probably photo-electric in character. This secondary radiation ultimately penetrates to the line AB and increases the conductivity of the gas there, thus facilitating the passage of the spark. The explanation was suggested by the recent work of Sir J.J. Thomson* on the action of low velocity ions.

If this hypothesis is correct, it should be possible to effect a lowering of the sparking potential even when the radiating point is "invisible" from the path of the spark, so long as some part of a sphere of radius 3 cm. about the point as centre is "visible" and within about 1 cm. from the spark line. To investigate this the following experiment was tried:-

The point C (Fig.9) was sheathed in an open cylinder of clean paraffin-wax and brought up to the gap in the position shown in the diagram. C was "invisible from any part of the spark AB, yet a distinct effect was observed. It follows, therefore, that the ionized air in the shaded portion of the diagram was able to cause a lowering of the sparking potential. It is to be noted, however, that a straight line is necessary from C to within less than 1 cm. from AB. A striking example of this type of action is observed when the point gap of Fig.1f is used. Here the effect will <u>only</u> occur if C and D are so close to A and B that no straight line can be drawn to the path of the spark, the radiation emanating from the silent discharges between C and A and between D and B.

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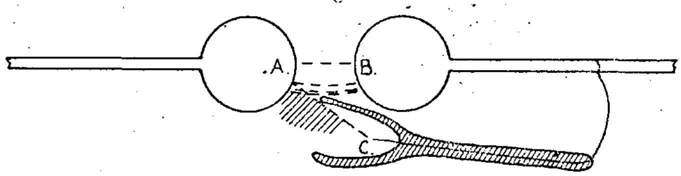
*Phil. Mag. vol.ii. p.675 (1926).

Fig. 9.



<u>Experiments with the Metallic Point connected to a Source of Constant Potential.</u>

When the metallic point C (Fig.1b) was connected to one pole of a Wimshurst machine instead of to one electrode of the main gap, the point was found to have only a slight effect in facilitating the passage of the spark across the main gap AB. The effect was much smaller than the usual three-point effect. It was also noted that no violet glow could be detected round the point in the dark, amd if two such points were connected to the opposite poles of the Wimshurst, no spark could be produced between them. No evidence was found of radiation proceeding from the point under these con--ditions, although careful tests were made with the ionization x chamber. The reason probably is that the point never reached a sufficiently high potential, the charge leaking from the point very rapidly in the form of the electric wind.

Somewhat similar results were found by Dr.J.D.Morgan*. That writer also concluded that no radiation was given off by a metallic point connected to the pole of a Wimshurst machine, and that any effect in the main gap in these conditions is due to an ionized stream, proceeding from the point. The experimental results of Morgan are therefore confirmed by the present experiments, but a somewhat different explanation of them is now offered. It was suggested by

*Phil. Mag. vol.iv. p.91 (1927).

Morgan that in order that a point should emit an ionizing radiation, its potential should be of an impulsive or transient character. The present writer agrees with this view, but is of the opinion that the transient nature of the potential is only necessary in order that the point should be raised to a sufficiently high poten--tial. With a continuous source the potential of the point never reaches a value high enough for the emission of radiation. It does not seem probable that the emission of radiation can depend, as Morgan suggests, on the time rate of change of potential of the point, but it does depend, as the present experiments have shown, on the space rate of variation of potential near the point.

The Influence of the State of the Cathode Surface on the Effect of the Ionizing Radiations.

A series of experiments was carried out with the object of deter--mining whether the action of the ionizing radiation in lowering the sparking potential of the main gap was affected in any way by the state of the cathode surface. In these experiments the two main electrodes were of course entirely shielded from any direct (photo-electric) radiations from the metallic poimts, the air gap between these being alone in a direct line with the discharge. Otherwise the arrangement of Fig.1d was used. In these circumstances it was found that the state of the surface of the cathode was an important factor in the action. If the cathode surface was dirty or oxidized, the point produced no effect if further than 2.6 cm. from the main gap (AB=1 cm.). When the cathode surface was cleaned by rubbing with emery paper, the limiting distance of the point was slightly over 3 cm. When the cathode surface was brightly polished, the limiting distance was over 4 cm. Experiments in which different metals were used as main electrodes also led to the same conclu-sion. With a brass cathode the effect was slightly less than with zinc, while with a cathode of copper (whether polished or not) the limiting distance of the point never exceeded 2 cm. These experiments show that, even when no radiation from the metallic point reaches the surface of the cathode directly, the effect of the radiations in lowering the sparking potential depends on the nature of the cathode surface. It was difficult to determine whether the anode surface had any such effect, but, if so, it was certainly much smaller than the effect of the cathode surface.

<u>Mechanism of the Spark Discharge.</u>

One of the chief facts which emerge as a result of the experiments described is that ions produced at some distance from the line in which the main spark passes can in some way facilitate the passage of this spark, and that the intensity of this effect depends upon the nature and state of the cathode surface. These results seem to be in entire agreement with the theory of the spark discharge recently proposed by J.Taylor* and based upon Sir J.J.Thomson's researches on the action of low velocity positive ions†. An essen-tial feature of this theory is that the positive ions in a low-pressure discharge, when neutralized at the cathode surface, give rise to ultra-violet (Schumann) radiations, and that these radia-tions, acting as an intermediate cause, produce the liberation

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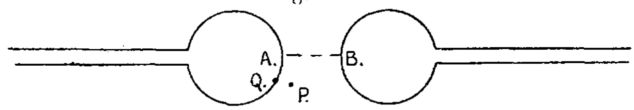
*J.Taylor, Phil. Mag. iii. p.753 (1927); Proc. Roy. Soc. A,114, p.73 (1927); 'Dissertation', Utrecht (1927).

†Phil. Mag. xlviii. p.1 (1924), and <u>loc</u>. <u>cit</u>.

of photo-electrons.

In the present experiments a positive ion formed at P (Fig.10), at some distance from the line of spark, AB, is moved under the

Fig. 10.



influence of the intense field to near the point Q of the cathode surface. There it excites ultra-violet radiation which liberates electrons from the metal in the neighbourhood. These electrons travel towards the anode surface, causing ionization by collision with neutral molecules in their paths. The process may repeat itself many times before the disruptive discharge takes place. Further evidence in favour of this theory is given by the point discharge itself. As the experiments have shown, electromagnetic radiations of fair intensity emanate from the parts of the dis--charge path near the points. These radiations are undoubtedly due to the liberation of the kinetic energy of the ions. The differ--ences between the discharge between points and the discharge between spheres are of degree rather than of kind. The field of force in the former case is much more irregular, and the surface density of the electricity is greater in the case of a point than in the case of a sphere, but the discharge mechanism is similar in nature. Consequently if radiations emanate from the point dis--charge, it is to be expected that radiations of the same type but of less intensity will be present near the spherical electrodes. That the visible radiations from a point discharge can also be obtained from spheres just before sparking takes place was shown many years ago by Walter*. The latter took photographs of sparks on rapidly moving plates, and found that each spark was preceded by a faintly luminous brush discharge. It is highly probable, therefore, that ultra-violet radiations are present near the spherical electrodes when the potential approximates to that required for a spark to pass.

From these considerations, then, the conclusion may be drawn that the action of metallic points on sparking potentials is similar to the action of the discharge itself. The behaviour of ions in the line along which the spark passes must be similar to the behaviour of ions outside of this line but within the intense field of electric force. If this is so, then the current through the gas must depend on the nature of the cathode surface, and some sort of photo-electric action must be assumed to take place. This is the conclusion to which the experiments of Taylor have led: it is not a accounted for in Townsend's theory of the spark discharge, in which the positive ions are assumed to produce others by collision with neutral molecules, but not as a result of their impact on the negative electrode.

That Taylor's hypothesis leads to a formula which gives accurately the current through a gas, when recombination of ions can be neglected, was shown by Townsend himself†, while in 1923 Dubois ‡

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*Wied. Ann. lxvi. p.636; lxviii. p.776.

†'Electricity in Gases', pp.330,331.

‡Ann. de Phys. t.xx. p.222 (1923).

derived a formula which allowed both for ionization by the col--lision of positive ions and for photo-electric action of the latter at the negative electrode. Dubois' formula reduces to those given by Townsend when β or γ is made zero. It is

$$N = n_o \frac{(\alpha-\beta)\, e^{(\alpha-\beta)D}}{\alpha(1+\gamma) - (\alpha\gamma+\beta)\, e^{(\alpha-\beta)D}}$$

where D is the distance between the parallel plate electrodes. N, n_o, α and β have the usual meanings assigned to them by Townsend, while γ is the average number of electrons liberated when one positive ion is neutralized at the cathode surface.

It appears to the writer that the problem of deciding between the "ionization by collision of positive ions" theory and a "photo-electric" theory of sparking potentials resolves itself in general into the question whether radiation or ionization by collision occurs first in a discharge. It is known that a collision between an ion and a gas molecule can give rise to a pulse of electromagnetic radiation. It is also known that a collision between an electron and a molecule can cause ionization of the molecule. But even assuming that the collision between a positive ion and a molecule can cause ionization, it must still be asked whether radiation or ionization will occur first as the speed of the positive ion is gradually increased. It would appear reasonable to suppose that less energy is required to move an electron from one orbit to another (as when radiation is emitted) than to remove an electron from the molecule entirely (as when ionization occurs); consequently it appears reasonable to conclude that radiation occurs before ionization.

If this view is correct, there can be little doubt that the photo-electric theory is true, since sufficient ions can be generated by this means to satisfy the requirements of the sparking current. If, on the other hand, ionization occurs first, then the photo-electric effects will be very subsidiary and of little importance.

It is again urged that the point discharge and the usual spark discharge between spheres or planes differ only in degree. What is found in the one may be expected to be found in the other with appropriate modifications. But the point discharge gives evidence of radiations from the vicinity of the cathode long before a spark passes. We may therefore expect that the same occurs in a modified way in the spark discharge between planes. It may be remarked in passing that one of Townsend's objections to a theory of the discharge in which the positive ions only form others at the cathode, is that the current from a positive point to a negative plane cannot be explained on this hypothesis. In view, however, of the fact that a positive point is the source of electromagnetic ionizing and photo-electric radiations, quite sufficient to account for the current in these conditions, it would scarcely seem necessary to assume any ionizing action of the positive ions in the point and plane system.

CHAPTER 2.

The Ultra-Violet Radiations Emitted by Point Discharges.

Introductory.

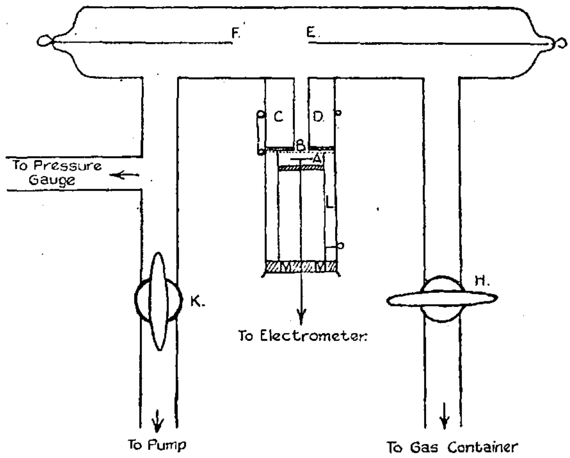
The fundamental result of the investigations described in the previous chapter was made the starting-point for the second series of experiments. That result might be described as follows:- Ultra-violet radiations of very short wave-length are emitted by the air in the vicinity of metallic points charged to a high potential. These radiations are of such frequency that they ionize air through which they pass. They are, however, very easily absorbed in air at atmospheric pressure, a fact which indicates that they lie between the soft X-ray region of the spectrum and the Schumann region of the ultra-violet.

The experiments described in the present chapter 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, as far as the writer is aware, no attempt has so far been made (with the possible exception of Miss Laird's work in America) 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.

Experimental Arrangements.

The final form of the apparatus used in the investigation is represented diagramatically in Fig.1.

Fig. 1.



The tube containing the points E and F between which the discharge was to pass was cylindrical in form, the platinum electrodes being placed along the axis of the cylinder. The detecting and measuring apparatus was contained in a side tube placed opposite one of the platinum points E, while the other two side tubes were fitted with stop-cocks K,H. One tube was branched between the stop-cock K and the discharge tube.

The detecting apparatus consisted essentially of a photo-electric cell, the insulated electrode of which was connected to a tilted electroscope or to a Dolezalek electrometer. C and D were two half-cylinders of brass of length 20 mm., sealed to the walls of the tube so that their faces formed the sides of a slot of width 4 mm. A potential difference of 560 volts was maintained between C and D during the course of the experiments. This strong electric field (X=1400 volts/cm.) was necessary in order to remove any ions which might drift or be projected down the slot towards the photo-electric cell. Theoretically the electric field was sufficiently strong to remove a simple positive molecular nitrogen ion projected into the slot with a speed of 3.10^7 cm./sec. Experiment showed that at pressu -ures of 5 cm. of mercury and upwards no ions of any kind penetrat- -ed to the cell.

B was a piece of fine-mesh phosphor-bronze wire gauze placed across the tube and insulated from C and D by two half-cylindrical plates of ebonite. This gauze formed one electrode of the cell. Pressed against it was the brass cylinder L which contained the other insulated electrode A. This electrode consisted of a small rect- -angular copper plate covered on the side facing the slot with a thin film of copper oxide. The latter, though less sensitive to ultra-violet light than other substances, suffers less from photo-electric fatigue, and consequently could be relied upon to give results which would be comparable over a long period. This plate was placed at a distance of about 2 mm. from the gauze and solder- -ed to a thin copper wire which was imbedded in pure paraffin wax and led down the axis of the cylinder L to the electroscope or electrometer. The latter was placed at a distance of about 2 metres from the tube itself. It will be observed, therefore, that the insulated electrode and the lead (surrounded by earthed tubing) from it to the measuring instrument were well shielded from effects due to induction. This was tested experimentally before any measurements were made. The insulation also was tested and proved to be of high quality. Finally the side tube containing this apparatus was completely sealed at M with a mixture of bees- -wax and resin.

The detecting cell therefore consisted of the gauze B, the cylinder

L, and the insulated plate A, while the slot between C and D limited the radiation affecting it to a small pencil from the immediate vicinity of the point E. The connections to C, D and B were made by platinum wires sealed into the glass tube.

The other side tubes provided a means of controlling the nature and pressure of the gas in the discharge tube. One tube was connected through a capillary to a gas container, while the other was connected to an oil pump. The branch in the latter tube was sealed to a vertical tube dipping into clean mercury, so that the pressure of the gas could be measured almost directly at any time. Since pressure measurements did not require to be very accurate, such a gauge was sufficient for the purpose. All the connections were sealed with the beeswax mixture which was found to be very satisfactory for work at pressures greater than 0.1 mm. of mercury.

The potentials relative to the earth of the half-cylinders C and D, and of the gauze B and the cylinder L, depended on the particular nature and purpose of each experiment. When observations were being made with the tilted electroscope to measure the photo-electric or ionization current, the half-cylinder C, the gauze B and the cylinder L were all at earth potential, while the plate A was charged to ±12 volts. In the later experiments in which the Dolezalek electrometer was employed, C, B, and L were maintained at ±250 volts, while the plate A was initially at earth potential.

The current across the discharge tube was supplied by a large induction coil (10-inch spark) used in conjunction with a motor mercury jet interrupter. Such an arrangement, when used to produce peak potential differences corresponding to spark lengths of less than half an inch in air at atmospheric pressure, gives a remark--ably steady mean current through the secondary of the coil. This current was measured by a Gaiffe milliamperemeter, and could be controlled to 0.1 milliampere. In order to eliminate as far as possible any inverse current through the coil, the battery E.M.F. in the primary circuit was kept as small as possible. Experiment indicated that the current at "make" was negligible.

Four gases were employed in the experiments to be described)-- oxygen, carbon dioxide, nitrogen and hydrogen,--- and of these, only the two latter were used in quantitative investigations. The hydrogen and oxygen were prepared by electrolysis; the nitrogen was prepared by the action of ammonium chloride on potassium nitrite in concentrated solution, and was purified by passing it through concentrated sulphuric acid and over red-hot copper filings; the carbon dioxide was prepared by the action of dilute hydrochloric acid on marble chips. No attempt was made (to begin with) to dry any of these gases.

The instruments used to measure the photo-electric currents and the ionization currents have already been mentioned. The tilted electroscope, being easy to adjust, was used in the preliminary investigations, but all the quantitative experiments were performed with the Dolezalek electrometer. The suspension used in the latter was a fine quartz fibre which was thoroughly platinized by placing it near the platinum wire cathode in a low-pressure discharge. The conductivity of the suspension was thus permanently ensured, and it was verified that the sensitivity of the instrument remained constant. During the work to be described the deflection of the needle due to one volt potential difference between the quadrants corresponded to 960 mm. on the scale, which was 3 m. from the instrument.

<u>Ionization and Photo-Electric Currents in Different Gases at Atmospheric Pressure.</u>

(1) <u>Oxygen</u>.- No results were obtained in oxygen on account of a peculiar phenomenan exhibited by the gas. As this phenomenon is one which might invalidate any ionization experiments carried out in this gas, it may be well at this point to describe it briefly. With the apparatus described in the previous section and the tilted electroscope as the detector of ionization, the normal conductivity of the gas at A was observed. This was very small. Then a spark discharge at atmospheric pressure was passed across the gas between E and F, a current of about 1 milliampere flowing for about one minute. The discharge was then discontinued, and again the leakage of the electroscope was observed. It was found that the gas in the vicinity of the insulated electrode A had become conducting, the rate of leakage of the electroscope being about one hundred times as great as before. The apparatus was now allowed to stand, the same gas being left in the tube, and the rate of leak of the electroscope was read at half-hour intervals. The leakage gradually and consistently decreased, until, twenty-four hours after the passing of the discharge, the rate of leak was the same as that observed at the beginning of the experiment.

On account of the strong electric field in the slot between the half-cylinders C,D, it was impossible for any charged particles to penetrate from the discharge between E and F to the plate A. Hence it must be concluded that the conductivity of the gas at A was caused by ionization which took place in the vicinity of A. This conclusion was verified by another experiment performed in a specially constructed tube, where all the ions directly produced by the discharge were immediately removed by a strong electric field. Spontaneous ionization of the gas continued to take place for some hours after the discharge had passed.

It is suggested that this ionization accompanies the gradual change of the O_3 molecule (and perhaps others) formed during the spark discharge to the normal O_2 molecule. It is immediately obvious that no experiments on the ionization produced by electromagnetic radiation could be performed in this gas with the apparatus describ-ed.

(2) Carbon Dioxide.- The ionization and photo-electric currents in this gas were exceedingly small. At atmospheric pressure the current at A was comparable with the normal leakage of the apparatus, and consequently any observations taken would be of little value. Even at the comparatively low pressure of 30 cm. of mercury the currents were still small, and investigation of the effects in carbon dioxide was therefore postponed until a later date.

(3) Nitrogen.- This gas, when purified, showed no signs of the phenomenon just described as occurring in oxygen, but a trace of oxygen in the gas was sufficient to give an observable effect. The nitrogen was therefore purified and repurified until all trace of the effect had vanished. The first experiment was made for the purpose of obtaining a table of ionization and photo-electric effects from the vicinities of the anode and cathode in the discharge tube. It was hoped that this table might be comparable

with that given in the first chapter (p.19).

The tube was therefore filled with nitrogen at atmospheric press--ure, all other gases having been excluded. The direction of the current in the primary of the coil was arranged so that E was the anode of the discharge, and readings were taken of the rate of leakage of the electroscope when the leaf, and therefore A, were charged to +12 and -12 volts relative to the earth. One milliampere was flowing from E to F. Then the direction of the current in the coil was changed, E becoming the cathode. The same readings were taken of the rate of discharge of A when charged to +12 and -12 volts. A great many difficulties were met with, one of the most important being the rise in temperature of the gas due to the discharge. Finally, the procedure adopted was to allow 15 min. to pass between each reading of the ionization current, and to flood the discharge tube with new gas before each reading. This allowed the tube to cool to room temperature between each discharge, and also eliminated any errors due to change in the chemical nature of the gas during the passage of the spark. The results, which have been verified with many samples of gas, are shown below; the figures in the last column are accurate to about 10%.

Potential of A in volts.	Nature of E.	Rate of Discharge of A.
+12	Anode.	4
+12	Cathode.	5
-12	Anode.	9
-12	Cathode.	9

Comparing these results with those obtained under different conditions and described in the last chapter, it must be concluded that the radiations in the two cases are of the same nature and have the same origin. Briefly, the differences between the two tables are exactly such as were anticipated from a consideration of the differences in the conditions. In the experiment just described a current of one milliampere was flowing in the discharge; in the former experiment the current was of the order of one microampere. The larger current might be expected (a) to intensify the radiations (as shall be shown later), (b) to partially level out the electric field in the gap, and so cause the intensity of the radiations from the vicinity of the cathode to increase. The first experiment was performed in air, the second in pure nitrogen. This appears to have caused little change in the total effect; and since these radiations are molecular or atomic properties, this is just what might be expected.

(4) Hydrogen.- Pure hydrogen, like nitrogen, is free from the spontaneous ionization effect observed in oxygen. The experiments performed in nitrogen, which have just been described, were repeated in hydrogen, and the table shown below indicates the results. The currents in hydrogen were larger than those in nitrogen, and the figures in the last column can be compared directly with the corresponding figures for nitrogen.

Potential of A in volts.	Nature of E.	Rate of Discharge of A.
+12	Anode.	4
+12	Cathode.	8
-12	Anode.	6
-12	Cathode.	16

Variation of Ionization and Photo-Electric Currents with Pressure in Different Gases.

The next series of experiments was designed to show how the effects of the radiations from each gas varied with the pressure of the gas. The experimental arrangements which have already been describ-ed were used, the Dolezalek electrometer being adopted as the current measuring instrument. Readings were taken of the ionization and photo-electric currents at A, the insulated electrode, at different pressures, when one milliampere was flowing across the gas between E and F. Two sets of readings were taken: (i) when the gauze B and cylinder L were at -250 volts relative to A; (ii) when the gauze and cylinder were at +250 volts relative to A. In all cases E was made the cathode, as it was found that the currents from the anode were unsteady.

In case (i) the currents measured by the electrometer represented the ionization currents at A. No photo-electric effect took place owing to the large negative potential of B; any photo-electrons emitted by B travelled to D under the action of the stronger electric field between B and D. Also since the field between A and B was 1250 volts/cm., the current measured was the saturation current for the gas, and was directly proportional to the number of ions formed between A and B.

In case (ii) the currents measured by the electrometer represented the sum of the photo-electric and ionization effects, each giving its saturation current. Therefore, by subtracting the readings taken under conditions (i) from the readings under conditions (ii), it was possible to obtain a measure of the pure photo-electric effects of the radiations.

The procedure while taking these observations was important, as on it depended the reliability of the results. It was as follows:-

(a) With the insulated quadrant of the electrometer earthed, and x all the electrical connections to C, D, B, and L broken, the discharge tube was exhausted.

(b) The tube was flooded with the pure gas to the required pressure.

(c) The connections to C, D, B, L were made, and the discharge across EF was started, the current being adjusted to one milli--ampere.

(d) The pressure of the gas was observed.

(e) The electrometer quadrant was insulated, and the ionization current was read by noting the time taken by the image to move over 150 divisions on the scale.

(f) The quadrant was earthed, and the pressure of the gas observed. The pressure at the time of reading the ionization current was the mean of the two observations.

(g) The discharge was stopped and the apparatus allowed to stand for 15 minutes.

This procedure was repeated with every observation of the current and pressure.

Hydrogen.- In Fig.2 below are given the curves obtained in hydrogen by the experiments just described. The ordinate represents in the case of curve (a) the ionization current, in the case of curve (b) the ionization current plus the photo-electric current. Curve (c) has been obtained by subtracting the ordinate of (a) from the ordinate of (b), and therefore represents the photo-electric current alone.

Fig. 2.

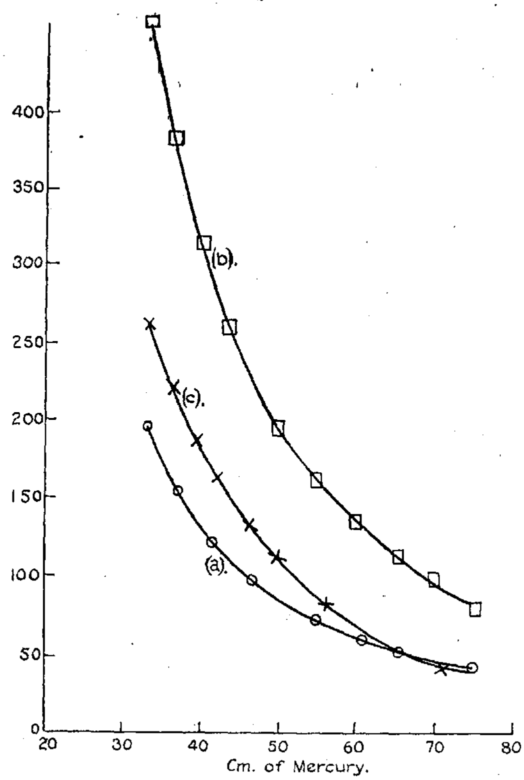
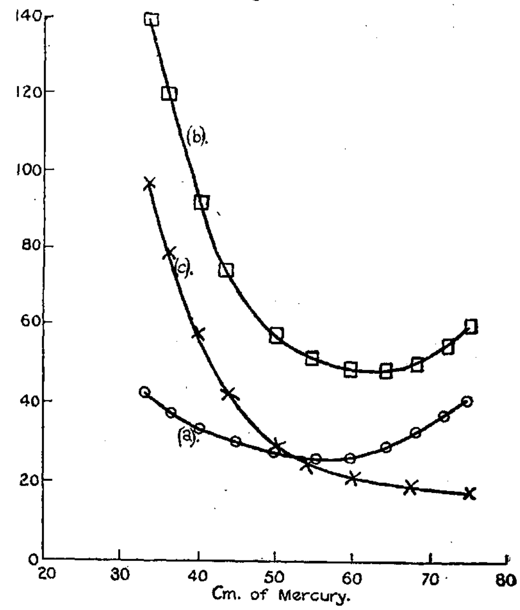


Fig. 3.



<u>Nitrogen</u>.- The corresponding curves for nitrogen are shown in Fig.3 above. Again (a), (b), (c) refer to ionization current, ionization current plus photo-electric current, and pure photo-electric current respectively. The scales in Figs.2 and 3 are the same, so that the relative effects in the two gases are shown directly.

<u>Variation of Ionization Current with Discharge Current.</u>

The next experiments were performed to investigate how the ioniz--ation current at A varied with the current flowing between E and F, the pressure being kept constant. These observations were made in the same manner as those already described, viz., a new sample of gas was used at each reading, and the gas was kept at room

temperature by allowing a 15 minutes' pause after each observation. The results are indicated by the curves shown below (Fig.4), where the abscissa measures the current across EF in milliamperes, and the ordinate the ionization current in arbitrary units.
Curves (a) and (b) refer to nitrogen, (a) being taken at a pressure of 25 cm. of mercury and (b) at a pressure of 33 cm. Curves (c) and (d) refer to hydrogen. (c) was taken at 37 cm. and (d) at 48 cm. All these curves were obtained with the gauze system charged to -250 volts, so that no photo-electric effect could take place.

Fig. 4.

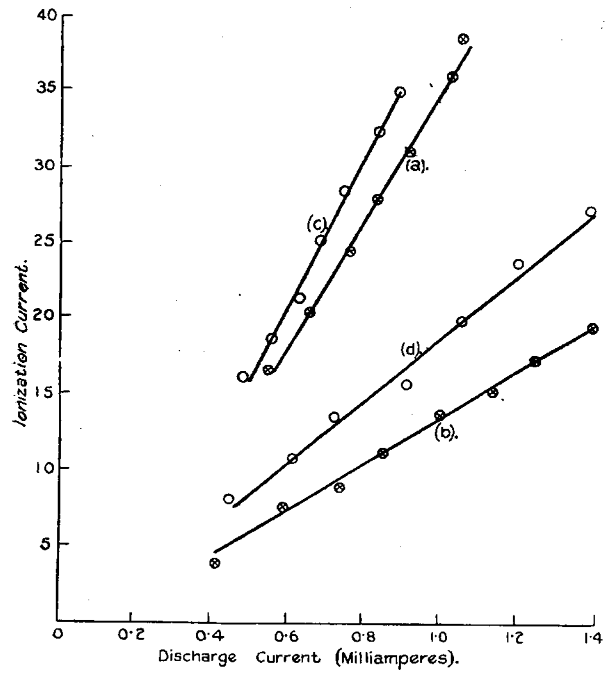
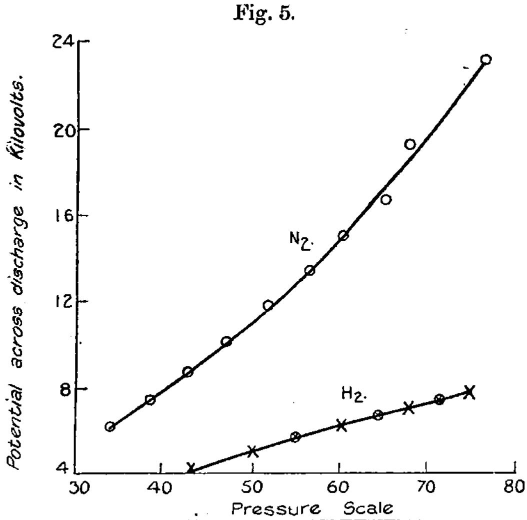


Fig. 5.



Variation of Peak Potential Across EF with Pressure.

The arrangement used for determining the peak potential across the discharge tube was a spark-gap placed in parallel with the discharge. The electrodes of the gap were zinc spheres of diameter 2.5 cm., carefully cleaned with fine emery-paper. The discharge across EF was maintained at one milliampere, and the pressure of the gas was observed. Then the spark-gap was slowly closed until a spark just passed. The pressure of the gas was again observed and the discharge stopped. The parallel gap was measured to .005 cm. by means of a reading microscope. The pressure of the gas was the mean of the two readings taken. The results for this series of observations in nitrogen and hydrogen are shown above (Fig.5), where the ordinate represents the peak potential across the gap in kilovolts, and the abscissa the pressure in cm. of mercury.

Discussion of Experimental Results.

The Ionizing Potentials of Hydrogen.- The ultra-violet spark spectra of hydrogen are well known. Under different conditions the gas emits two line spectra, stretching from 1670 to 900 A.U., and two continuous spectra. There is still considerable doubt as to the lowest ionizing potential of the gas. Many observers record ionization occurring at a potential of 11 volts, but this value has been questioned by Horton and Davies*, who suggest that it is due to the presence of mercury vapour in the apparatus. The most

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*Phil. Mag. vol. xlvi. p.872 (1923).

generally accepted lowest value is 16 volts, which is said to corre -espond to the formation of H_1^+ and H_1^- from H_2; that is, to ioniz- -ation plus dissociation. F.L.Mohler*, on the basis of his own experiments, concludes that "there is no evidence that hydrogen emits radiation which is capable of ionizing the normal molecule," and, as he points out, since no hydrogen lines have been observed beyond 885 A.U., this appears reasonable if the lowest ionizing potential is 16 volts. All the experiments performed in hydrogen and described in the present thesis, however, indicate a strong ionization of the gas by its own radiations. The problem arises- was the ionization observed due to the water-vapour content in the gas? At the time of writing this problem is still being invest- -igated: all that can be said here is that ionization still takes place when the hydrogen (prepared from barium hydroxide by elect- -rolysis) is dried by liquid air. In one experiment the ionization current actually increased as water-vapour was removed from the gas.

If the observed ionization was due to the hydrogen itself, two conclusion are possible. Either the gas possesses a lower ionizing potential than the accepted one (16 volts), or it is capable of emitting radiations of shorter wave-length than those examined until the present. If the latter conclusion is correct, the radia- -tions are molecular in origin, since the limit of the Lyman series, $N\left(\frac{1}{1^2}-\frac{1}{m^2}\right)$, which is the atomic radiation of greatest frequency, corresponds to a potential of 13.5 volts.

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*Proc. Nat. Acad. Sci. xii. p.494 (1926).

<u>Variation of the Ionization Current with the Discharge Current, the Pressure being Constant</u>.- The ordinates of the curves collected in Fig,4 measure the ionization currents at A. Since the pressure remained constant, and the currents measured were of saturation value, they may be taken to represent the intensities of the ionizing radiations. Therefore the curves show the variation of the intensity of the radiations with the current flowing between E and F, They indicate quite definitely that the intensity of these radiations increases linearly with the discharge current. Therefore, if it is assumed that the mean frequency of the radiations does x not change with change in the current density, it may immediately be stated that, since the potential across EF remains constant, <u>the pressure of the gas being constant, a constant fraction of the energy dissipated in the discharge (for the energies investigated) is transformed into ionizing electromagnetic radiation.</u>

Whether this remains true for very small or very large currents still remains to be investigated, but certain significant points emerge from a consideration of the curves already obtained. The gradients of the lines (a) and (c) are definitely greater than the gradients of the lines (b) and (d), while the curves, if pro--duced, cut the discharge current axis at different points. The difference between the two pairs of curves is that (a) and (c) were taken at a lower pressure than (b) and (d).

The fact that the gradients of the curves (a) and (c) are greater than the gradients of the curves (b) and (d) is suggestive. This means that, as the pressure diminishes, the same increase in the current density at E produces a larger increase in the radiations detected at A. This may be due to either or both of the following causes:-

(i) Owing to the increase in the mean free paths of the gas ions with the decrease in the pressure, a greater percentage of the total number of ions carrying the current may excite radiation in the gas. If this is correct, the total intensity of the radiations at their source will increase as the pressure is diminished, a constant current being maintained across EF.

(ii) The same change in the intensities of the radiations may occur at the source at all pressures, when the discharge current is changed by the same amount, but the change in the intensity at A will be smaller the higher the pressure, owing to the greater absorbing power of the gas.

No matter what the cause of these variations is, it is at least evident, as has been shown, that, for the currents investigated, C=Li+M, where C is the ionization current measured at A, and ~~fixx~~ i is the current flowing across EF. L and M are constants when the pressure is constant, but L at least must be a function of the pressure, p. Taking the simplest assumption first, let

$$C = i\,\phi(p).$$

Then

$$\frac{\partial C}{\partial i} = \phi(p).$$

and therefore

$$\frac{\left.\frac{\partial C}{\partial i}\right]_{p=p_1}}{\left.\frac{\partial C}{\partial i}\right]_{p=p_2}} = \frac{\phi(p_1)}{\phi(p_2)} = \left.\frac{C_1}{C_2}\right]_{i=\text{constant}} = \frac{m_1}{m_2}.$$

where m_1 is the gradient of the line $C=i\phi(p_1)$, and m_2 is the gradient of the line $C=i\phi(p_2)$. But from the curves of Figs.2 and 3, $\frac{C_1}{C_2}$ may be determined. For the case of hydrogen $\frac{m_1}{m_2}=2{\cdot}9$, while $\frac{C_1}{C_2}=1{\cdot}7$ for corres--ponding pressures. Therefore C is not of the form $C=i\phi(p)$. The supposition that $C=(i-K)\,\phi(p)$ is no more tenable, for again

$$\left.\frac{C_1}{C_2}\right]_{i=\text{constant}} = \frac{m_1}{m_2}.$$

It is therefore evident that the true form of the function must be

$$C = i\,\phi(p) - \psi(p) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1).$$

Then $\frac{\partial C}{\partial i} = \phi(p)$,

and $\frac{m_1}{m_2} = \frac{C_1 + \psi(p_1)}{C_2 + \psi(p_2)}$.

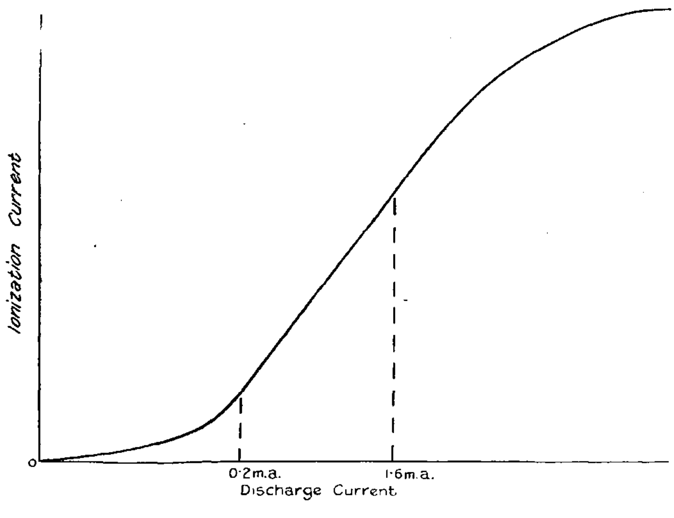
If $\psi(p_1) > \psi(p_2)$,

in general $\frac{m_1}{m_2} > \frac{C_1}{C_2}$.

The graphs of Fig.4 indicate that $\psi(p_1) > \psi(p_2)$, and are therefore in agreement with this hypothesis. It may be remarked at this point that it is proposed in later work to evaluate $\psi(p)$ for many different values of p by observations similar to those shown in Fig.4. In this way it is hoped that the forms of both functions will be exhibited. Reasons will be given later which suggest that the form of $\frac{\phi(p)}{\psi(p)}$ should be interesting.

It must be observed that the theory which has just been given only applies to a limited range of discharge current (0.4 to 1.5 milli-amperes). It is very improbable that the linear relation between C and i will hold for very small currents, as C would then be zero when $i = \frac{\psi(p)}{\phi(p)}$. Possibly the complete form of the C, i curve is as shown below in Fig.6.

Fig. 6.



Variation of Ionization and Photo-Electric Currents with Pressure in Different Gases.- Figs.2 and 3 represent the variation with pressure of the currents at A in hydrogen and nitrogen respectively. The pressure was varied from about 76 cm. of mercury to about 30 cm. as this region was the most difficult to investigate (owing to the small values of the currents) and at the same time the most inter--esting.

The curves in nitrogen are entirely different from those in hydrog--en, except perhaps in the case of the curves giving the pure photo-electric effects, which are at least similar in form. The currents in hydrogen continually decrease with increase of pressure; both experimental curves in nitrogen exhibit a decided minimum at about 60 cm. of mercury.

As the problem of interpreting, and, if possible, explaining these results is exceedingly complicated, it may be well to state at the outset in the most general terms the variables in the experiments. Broadly speaking, the variation with pressure of any radiations detected at A might be due to three factors, which are as follows:-

(i) Change in the total absorption of the gas between E and A.

(ii) Changes in the intensities of the radiations at their source E.

(iii) Changes in the frequencies of the radiations emitted at E.

Of these factors (i) is likely to be of the greatest and (iii) of the least importance, while (ii) and (iii) may be grouped together as changes in the character of the radiations from E.

Concerning the absorption of the gas between E and A, it is necess--ary to consider first how a monochromatic ultra-violet radiation of constant intensity I_{λ} at its source would vary in intensity at

A as the pressure of the intervening gas is changed. It is well-known that, for the visible spectrum and also for the X-ray region, the intensity at A might be represented by the expression $I_\lambda e^{-\alpha p}$, where p denotes the pressure of the gas, and α is a function of the frequency of the radiation. But for the region with which these experiments are concerned, namely that region producing intense ionization of the gas, this expression has not been verified, while for certain analogous cases concerned with the absorption of ultra-violet light by solutions, it is known that α is also a function of the concentration of the absorbing medium.

Let it be assumed, however, that the absorption of the radiation occurs according to the normal law. Let the loss of energy across a distance dx of the total distance EA be proportional to

(i) the intensity of the radiation at that point, I;

(ii) the density of the gas at that point, ρ.

Also, let the constant of proportionality (the absorption coefficient) be a function of the wave-length of the light, $\phi(\lambda)$.

Then
$$dI = -\phi(\lambda)\rho I\, dx,$$
and
$$I = I_\lambda e^{-\phi(\lambda) k p x},$$
where $\rho = kp$.

But the ionization current C is proportional to the loss of energy, as the radiation passes through 2 mm. of the gas near A.

$$dI = -\phi(\lambda) k p I_\lambda e^{-\phi(\lambda) k p x}\, dx,$$
$$\therefore C = K p \phi(\lambda) e^{-k p d \phi(\lambda)}, \quad \ldots\ldots\ldots (2).$$

where d is the distance EA.

Therefore, if the radiation from the vicinity of E were monochromatic, the current C would be a function of p of the form $C = \alpha p e^{-\alpha p}$, having a maximum where $p=\frac{1}{\alpha}$.

Needless to say, the radiations from A are not monochromatic, and the simple theory given above might be expected to be inapplicable to the experimental results on this ground alone. If, for example, the gas is supposed to emit a continuous spectrum, the absorption coefficient in the above analysis will not take a mean value for the spectrum. As the pressure is diminished, the relative inten--sities at A of the different parts of the spectrum will vary, owing to the dependence of α upon λ. If the law of variation of spectrum intensity at the source is $I_\lambda = F(\lambda)$, then the intensity of the spectrum at A will be given by

$$I = F(\lambda)\, e^{-\phi(\lambda)\, k p d};$$

and if the spectrum is continuous between the limits $\lambda = \lambda_1$ and $\lambda = \lambda_2$ (analogous to an X-ray impulse spectrum* where the intensity at λ_2 is very small), the total effect at A in terms of ionization current is

$$C = K\int_{\lambda_1}^{\lambda_2} p\, F(\lambda)\, \phi(\lambda)\, e^{-kpd\phi(\lambda)}\, d\lambda \quad \ldots\ldots\ldots (3).$$

Any attempts to evaluate $\phi(\lambda)$ and $F(\lambda)$ at this stage of the investig--ation must necessarily be purely hypothetical; but if it is assumed that the gas is a simple resonator of resonating wave-length λ_0, then, where no damping coefficient is introduced,

$$\phi(\lambda) = \frac{N\lambda^4}{(\lambda^2-\lambda_0^2)^2}.$$

Similarly, if it is assumed that the continuous spectrum is <u>exactly</u> analogous to the X-ray spectrum, beginning at $\lambda = \lambda_0$ and dying away towards $\lambda = 2\lambda_0$,

$$F(\lambda) \doteqdot \frac{(2\lambda_0-\lambda)(\lambda-\lambda_0)}{\lambda_0^2},$$

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*C.T.Ulrey, Phys. Rev. ii. p.401 (1918).

and

$$C = \int_{\lambda_0}^{2\lambda_0} \frac{p(2\lambda_0-\lambda)(\lambda-\lambda_0)\lambda^4}{\lambda_0^2(\lambda^2-\lambda_0^2)^2} e^{-\frac{kpd\lambda^4}{(\lambda^2-\lambda_0^2)^2}} d\lambda \ldots\ldots (4)$$

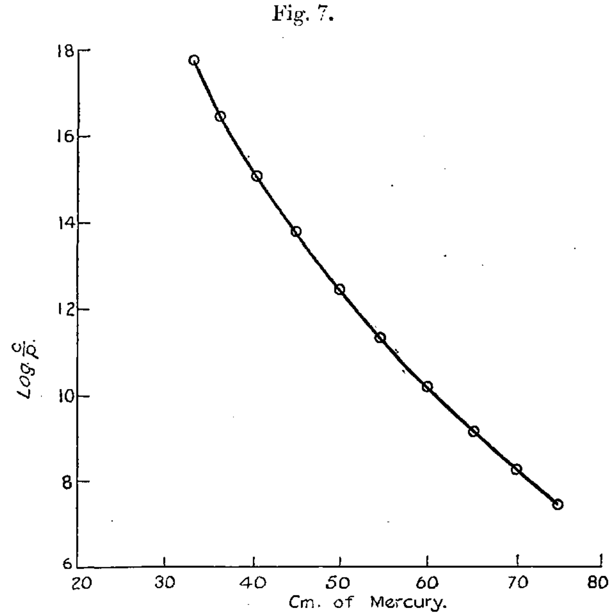
Neither equation (3) nor (4) can be used until more is known concerning the variables involved, and until they can be combined with the variations in intensity due to changes in the emissive power of the gas, for both are concerned wholly with absorption effects.

Qualitatively, however, the reduction of pressure might be expect--ed by the above theory to increase the current C. Certainly no minimum is to be expected in the curve, although a maximum is predicted by equation (2) at a pressure probably much below those investigated in the present experiments. The hydrogen curve (a) is not inconsistent with such a theory. The increase in the current with diminution of pressure is approximately according to the formula

$$C = Ap e^{-\alpha p} \ldots\ldots\ldots\ldots (2)$$

a small but consistent increase in the coefficient α being evident. Fig.7 exhibits the variation of $\log\frac{C}{p}$ with pressure for curve (a) of Fig.2.

Fig. 7.



So far the variables (ii) and (iii) in the experiments have been neglected. The shape of curve (a) Fig.2 has been examined wholly from the point of view of the absorption of the gas, and it has been implicitly assumed that the effects of variations in the intensities of the radiations at their source were negligible compared with the absorption effects. It now remains to be seen whether this assumption is justifiable or not.

Theoretically the reduction in pressure might be expected by in-creasing the mean free paths of the ions to increase the probab-ility of excitation of the shorter wave radiations. On the other hand, the decrease in the potential necessary to carry the dis-charge which accompanied the decrease of pressure might cause a corresponding fall in the potential drops across the free paths of the ions. As the mean free path λ is inversely proportional to the pressure, and the potential, as shown from Fig.5, is approx-imately proportional to the pressure, the product $X\lambda$ might be expected to remain constant, on the assumption that the field X in the vicinity of E is proportional to the potential across EF. If, however, the field at E is that due to the normal cathode fall, and is independent of the pressure, the probability of radiation accompanying the impact of ions must be inversely proportional to the pressure. Again, if the radiations are due to the impact of ions on neutral molecules, another point must be considered. For a given ionic current the number of molecules in the gap EF and therefore the probability of radiation will be proportional to the pressure. If the radiations are due to both ionic and molecular collisions, the expression for the intensity at the source will be the sum of <u>two</u> functions of the pressure.

In the preceding investigation it was found that the current at A was given by equation (1):

$$C = i\,\phi(p) - \psi(p) \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where $\frac{d\psi}{dp}$ was negative. This indicates that an important fraction of the radiation is due to the impact of ions on neutral molecules, since no other hypothesis could explain the existence of $\psi(p)$. If the simplest possible interpretation be given to the variation with pressure of the intensity I_λ of the radiations at their source

$$I_\lambda = Ai - \frac{B}{p}.$$

Then, assuming the theory leading to equation (2),

$$C = (Aip - B)e^{-\alpha p}.$$

and $\phi(p) = Ape^{-\alpha p}$, $\psi(p) = Be^{-\alpha p}$.

No matter what functions of <u>p</u> are used in the expression for I_λ, since $C = pI_\lambda e^{-\alpha p}$, it is quite reasonable to assume that the absorp--tion term $e^{-\alpha p}$ will be the most important; this explains why the absorption effects could be considered alone in the case of hydrogen.

To return to the absorption of the radiations, in the case of curve (a) for nitrogen, the theory which has been sketched does not apply. The absorption of nitrogen cannot follow the simple laws which appeared to fit the case of hydrogen, or else the quality of the radiations from the discharge must vary with the pressure in a peculiar manner. It has certainly been observed that the visible radiations from the discharge in hydrogen are entirely different from those in nitrogen. The greater part of the spark in hydrogen is blue in colour, <u>and its colour does not alter as the pressure is diminished</u>. The spark in nitrogen at atmospheric pressure emits radiations of all colours, and consequently appears white, bht as the pressure is reduced the discharge becomes almost entirely red. This may mean a shift of the maximum intensity of the radiations towards the red end of the spectrum; it may mean that the absorption of the gas has changed in such a way as to cut off the blue light. Neither explanation appears probable, but either is consistent with curves (a) and (b) of Fig.3.

That the maximum intensity of the radiations should shift towards the red end of the spectrum as the pressure is diminished is contrary to the results obtained by L.Hamburger*, who found that for the visible spectrum the maximum of the emitted light from nitrogen shifted towards the ultra-violet as the pressure was diminished. His experiments were, however, performed at a very much lower pressure than those described in the present thesis. It must also be observed that the curve (c) Fig.3, which gives the variation with pressure of the intensities of the radiations producing the photo-electric effects exhibits no minimum. Although the curve is not by any means exponential, there is a steady increase in the intensity as the pressure is reduced. This difference between the ionization current curve and the photo-electric current curve must be significant. It indicates that if the anomalous variation in curve(c) is due to absorption, the anomalous absorption affects only the shorter wave radiations, and then it is difficult to see why the appearance of the discharge should alter as the pressure is reduced. On the other hand, it agrees well with the hypothesis that the maximum intensity of the radiations moves towards the

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*K. Akad. Amsterdam, xx. Proc.7, p.1043 (1918).

infra-red, for then the photo-electric effect, being due to radiations of longer average wave-length than those causing the ionization effects, would suffer little change. On the whole, the evidence indicates that the difference between the curves for nitrogen and hydrogen is not due to the gases obeying different absorption laws, but is due rather to the difference between the modes of variation with pressure of the radiations emitted by the gases.