DISCHARGE FROM HOT CAO.

By C. D. Child.

IT was suggested a few years ago by Sir J. J. Thomson[1] that certain phenomena of electrical discharge could be explained by what we may call ionization by *repeated* impact. He had found that luminous discharge could be produced from a cathode of hot CaO with potential differences much smaller than those which are needed when a cold cathode is used, and that at a certain critical point it needed but a very small increase in the voltage to produce a large increase in the current and to change from the non-luminous to a luminous form of discharge. He believed that the ionization in the luminous form of discharge was not due to the breaking up of an atom by a single impact with an electron, but rather to an explosion of the atom because of its having absorbed so much internal energy from repeated impacts with electrons that its equilibrium had become unstable.

If this idea is correct, it is important not only because it explains this particular phenomenon, but also because it offers an explanation of the ionization of the arc and gives us some information concerning the character of the atom. I have, therefore, given some study to the subject, but find that there are several reasons for rejecting this explanation.

Improbability of Repeated Impacts.—The first of these objections is that there are far too few electrons present in the tube at any time before the discharge becomes luminous to occasion repeated impacts. For example, in one experiment performed by myself the largest current that could be passed through the tube without having a luminous discharge was 5×10^{-9} ampere, which is 150 electrostatic units. The charge carried by each ion[2] is 3.4×10^{-10}. The cross section of the tube used was approximately 5 sq. cm. So that the number of electrons passing through each square

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[1] Nature, 73, 496, 1906.

[2] Thomson's Conduction of Electricity through Gases, 2d ed., p. 158.

centimeter per second was 8.85×10^{10}. The pressure of the gas was .014 mm. and the mean free path of the electron at this pressure is approximately 3.76 cm.[1] So that in each cubic centimeter only 2.34×10^{10} electrons would hit molecules per sec.

According to Myers[2] there will be 11.2×10^{14} molecules per c.c. under these condition of pressure and temperature. From this we find that each molecule will on the average be hit once in 48,000 sec., or once in thirteen hours, and it only requires a fraction of a second to produce the luminous discharge when the conditions are right for it.

This is, of course, not an argument against ionization by repeated impact after the luminous discharge has commenced, for then the number of electrons will be very much greater, but the idea of such impact was used by Thomson as an explanation of the beginning of the luminous discharge, and it is an argument against such an explanation. There will, however, be other data given later which indicate that not at any time is there ionization by repeated impact.

Critical Condition Does not Depend on the Amount of Current, but on the Condition of the Cathode.—In the second place experiments indicate that the voltage required to change from the non-luminous to the luminous discharge depends but slightly, if at all, on the amount of current flowing, but does depend very greatly on the kind and condition of the cathode. That is, the number of electrons passing through the tube and hitting upon the molecules does not determine the point where the change occurs, while other conditions do.

The form of apparatus used for showing this is given in Fig. 1. *T* is a tube 2.8 cm. in diameter. *P* is the connection to the vacuum pump, McLeod gauge, and drying tube. *C* is the cathode consisting of platinum foil, approximately 2 mm. in width, 12 mm. long, and .02 mm. thick, the bottom being covered with CaO. This was welded to aluminum wires which led out of the tube and was heated by an alternating current connected at *c* and *c′*.

A is an iron anode, fastened to an iron wire which is brought down through the tube *a* into a mercury cup, so that the anode

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[1] Idem, p. 476.

[2] Myers' Kinetic Theory of Gases, p. 333.

could be raised or lowered. A shunt of 50 ohms resistance was placed across *cc′*. The middle of this, lettered *b*, had the same potential as the middle of the foil *C*. A potential difference was maintained between *b* and *A* by connecting them to *d* and *d′*, two points on a variable resistance through which a current was passed from a dynamo. By this means any potential difference from 0 to 130 could be used. *V* is a Weston voltmeter measuring this potential difference. *G* is a galvanometer measuring the current through the tube.

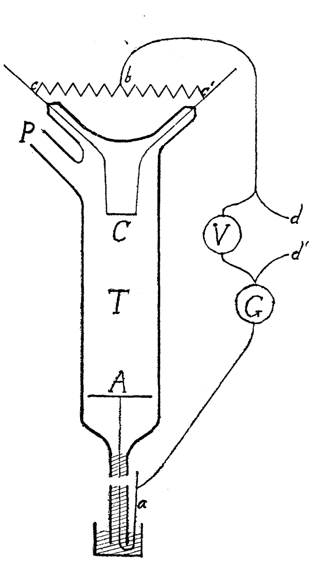

Fig. 1.

The first experiment was a comparison of the discharge from clean hot platinum with that from hot platinum covered with CaO. With clean platinum it is possible to get a large current without changing the character of the discharge, while with CaO it requires but a very small current to produce this change, the potential difference between the electrodes being the same in the two cases.

In order to get as large a current from the platinum as possible it is desirable to perform the experiment before the occluded gas has been entirely driven off. If this is done, the current is continually changing, so that no two sets of readings are the same, but this does not interfere with our present purpose.

The readings as taken are given in Table I., the first column giving the potential difference between the electrodes and the second the current. The platinum foil was a little more than red hot and the pressure of the gas was approximately .04 mm.

Table I.

Potential Difference in Volts.	Current in Amperes Times 10^{-7}.
71	.1
80	.5
84	2.1
90	6.5
125	48.2

There was here no abrupt change in the amount of current and the discharge was not at any time luminous. There is in some cases a slight luminosity with the discharge from clean platinum, but even then there appears to be no sudden increase in current nor sudden change from non-luminous to luminous discharge.

On the other hand with hot CaO the discharge changes to the luminous form before anything like this amount of current passes through the tube. This is especially true when the cathode is quite hot and has been used until the occluded gases have been driven off. In one case it was impossible to pass more than 5×10^{-9} ampere with a potential difference of 95 volts without the discharge becoming luminous. When the voltage was raised above this, the current became as large as an ampere or more, if the resistance in series with the tube was small.

Thus we see that the discharge remained non-luminous quite irrespective of the amount of current passing, provided the cathode was clean platinum and that it very quickly changed to the luminous form, if the cathode was very hot CaO.

Thomson states that he found the voltage at which the change took place to depend on the current, but in his experiments the current was changed by raising the temperature of the cathode. When that is done, it is not possible to decide whether the critical point depends on the current or on the temperature of the CaO. In the experiments described above it is made clear that it is the condition and temperature of the cathode that determines this point and not the amount of current.

The Potential Difference between the Beginning and End of a Striation.—The potential difference between the beginning and end of a striation was examined, hoping that it would throw some light on this question.

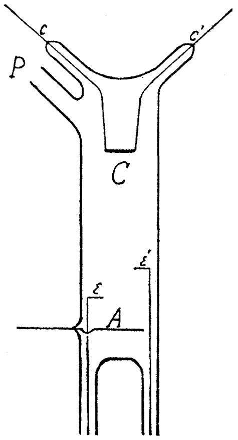

Fig. 2.

The tube was exchanged to the form shown in Fig. 2. Both A and C are here fixed; e and e' are two movable exploring electrodes which are connected to an electrometer. The vertical parts of these were covered with small glass tubes for a few centimeters near the top, so that only the horizontal ends would receive charges. These ends were platinum wires .5 mm. in diameter. They were placed as near as possible to the sides of the tube and did not appear to distort the striations. The main tube was 4.2 cm. in diameter. The distance between *A* and *C* was 8 cm. The length of a striation varied as the pressure of the gas was varied, but was in general in the neighborhood of 2.5 cm.

It was first of all observed that the potential difference which was being studied varied as the pressure of the gas was changed. This is shown in Table II. The first column gives the pressure of the air left in the tube, and the second the potential difference between the beginning of one striation and that of the next. The current was .02 ampere.

TABLE II.

Pressure of Gas in Millimeters.	Potential Difference in Volts.
.06	11
.08	12.9
.164	16
.38	23.5

It was also found that the striation potential difference depended on the amount of current flowing through the tube. This is shown in Table III., where the first column gives the current and the second the potential difference. The pressure in the gas was .06 mm. of mercury.

TABLE III.

Current in Amperes.	Potential Difference in Volts.
.00032	14
.00064	13.2
.01	12
.2	10

Since these experiments were performed an article has been published by Wehner,[1] giving the results of a full investigation of the striation potential difference when there was discharge from a cold cathode. His experiments on the change produced in this quantity when the pressure of the gas was changed were performed in hydrogen and the potential differences which he gives are lower than the ones given above, but they show the same kind of a change.

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[1] Ann. d. Phys., 32, 49, 1910.

In general he also found the same kind of a change when the current was changed. The changes, however, were through a much smaller range than that given here and were accordingly less noticeable. The lowest value which he found for the potential difference was 8.56 volts.

At first sight Table III. appears to give some reason for believing that ionization may take place more easily where there is a chance for repeated impact. Certainly it is true that where there is the greatest number of electrons passing through a gas, there is the smallest striation potential difference, and it is probable that this quantity is closely related to the potential difference needed to produce ionization by impact, as is suggested by Wehner.

But a second thought will hardly encourage such a view. The current was six hundred times greater in the last case given in the table than in the first. Each molecule would be hit six hundred times in one case where it would be hit but once in the other, and yet the potential difference decreased but a few per cent. It is certainly highly improbable that such a small change would occur, if repeated impact causes the molecules to be more easily ionized.

Certainly it is possible to suggest some more probable explanation. For example, when the larger current is flowing, the temperature of the gas must be much above that of the room. A small percentage of the electrical energy dissipated in the tube would be sufficient to raise the temperature of the gas several hundred degrees in a few seconds and it is altogether probable that at high temperatures the gas is more easily ionized than at low ones.

However, we will not be ready to give any explanation of these facts until we know more about what the facts are. For example, the lowest voltage here recorded was 10 volts, but Thomson states[1] that he found the potential difference between one striation and the next to be as low as 2.7 volts under certain conditions. He does not state what these conditions are, and I have not been able to get such a value. But until the phenomena have been more thoroughly examined, it is not possible to state what the cause of the relation between the voltage and the current is, and certainly we cannot say that these phenomena uphold in any way the idea that ionization occurs more easily when there is repeated impact.

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[1] Phil. Mag., 6, 18, 449, 1909.

Increase in Current not due Alone to Ionization in the Gas.—We have given reasons for believing that the change from the non-luminous to the luminous form of discharge is not due to ionization by repeated impact. We may go a step further and say that the change does not appear to be due alone to ionization of any kind in the gas. There is no question but that ionization by impact occurs, but there are reasons for believing that it is not the only cause producing the change.

There are two ways in which ionization in the gas can increase the current. It can increase the number of positive ions moving toward the cathode, or it can change the field near the cathode, so that all the electrons shall be drawn from it, instead of being driven back by the electrostatic repulsion of those which had previously been emitted.

That the great increase in the current cannot be accounted for by a movement of positive ions toward the cathode is shown by two lines of reasoning. The first is that the electrostatic effect on the positive ions would check any large increase in the current due to them alone.

The Electrostatic Effect Produced by Ions.—An electrostatic effect occurs whenever there are more ions of one kind than of the other in a given volume. This effect may become so large as to reverse the previous direction of the field and to limit very greatly the amount of current flowing. This is especially apt to occur when there are positive ions present, for their mass is much greater than that of the negative ions and their motion correspondingly slower.

The ratio of the mass of positive ions to their charge is approximately 20,000 times as great as the corresponding ratio for the negative ions.[1] As a result one positive ion going through a given space per second would neutralize the effect of 20,000 electrons. If there were more positive ions than this they would raise the potential of the region and tend to check their own movement.

It is not possible to compute just how many positive ions it would take to raise the potential so as to check the current when the cathode is an irregular piece of foil, but we may get some idea of what is to be expected by considering the current density between

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[1] Thomson's Conduction of Electricity through Gases, 2d ed., p. 149.

parallel plates of infinite extent, when there are only positive ions present. The less the ions are stopped by collisions with molecules, the greater will be their velocity and the less the electrostatic effect produced by the movement through the field of a given number. In order to find the maximum current, we may assume that there are no collisions. I have not been able to find any computation applying to this case, and hence have given it in the following paragraphs.

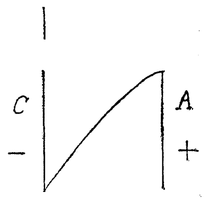

Fig. 3.

Let us assume that the plates A and C are of infinite extent, separated by a distance x_1. Let the potential of C be zero and that of A be V_1, and assume that there are at A an indefinitely large number of positive ions. The electric force will cause these to move toward C, producing a current.

Let I = the current flowing through a unit cross section,
n = the number of ions in a unit volume,
ϵ = the charge in electrostatic units carried by each ion,
m = the mass of each ion,
V = the potential in electrostatic units at any point at a distance x from C,
v = the velocity of the ions at a distance x from C,
ρ = the density of the electricity at a distance x from C.

$I = n\epsilon v$ = a constant, and the acceleration of the ions equals the charge times the electric force divided by the mass, or

$$\frac{dv}{dt} = -\frac{\epsilon}{m}\frac{dV}{dx}.$$

If we multiply this equation by the equation, $vdt = dx$, and integrate, remembering that the velocity is zero when V is V_1, we have

$$\frac{1}{2}v^2 = \frac{\epsilon}{m}(V_1 - V) \qquad \text{or} \qquad v = \left\{\frac{2\epsilon}{m}(V_1 - V)\right\}^{\frac{1}{2}}.$$

But

$$\rho = n\epsilon = \frac{I}{v} = \frac{I}{\left\{\frac{2\epsilon}{m}(V_1 - V)\right\}^{\frac{1}{2}}}$$

and if we assume that there is no variation in potential in directions parallel to the plate we have

$$\frac{d^2V}{dx^2} = -4\pi\rho = -\frac{4\pi I}{\left\{\frac{2\epsilon}{m}(V_1 - V)\right\}^{\frac{1}{2}}} = -\frac{k}{(V_1 - V)^{\frac{1}{2}}}$$

where k is a constant equal to $4\pi I/\sqrt{2\epsilon/m}$.

Multiplying this by the equation

$$\frac{dV}{dx}dx = dV$$

and integrating, we have

$$\frac{1}{2}\left(\frac{dV}{dx}\right)^2 = 2k(V_1 - V)^{\frac{1}{2}} + C.$$

The constant, C, equals the value of $\frac{1}{2}(dV/dx)^2$ at A. As the space between A and C becomes more and more filled with positive ions, the value of dV/dx approaches zero, and for the largest current which it is possible to have it would equal zero. For such a current we have

$$\frac{dV}{dx} = 2\sqrt{k}(V_1 - V)^{\frac{1}{4}}.$$

Further integration gives us

$$V = V_1 - (V_1^{\frac{3}{4}} - \tfrac{3}{2}\sqrt{k}\,x)^{\frac{4}{3}},$$

since $V = 0$ when $x = 0$. The curve in Fig. 3 between A and C represents such a distribution of potential as this.

Since V_1 is the value of V when $x = x_1$, we have

$$\tfrac{3}{2}\sqrt{k}\,x_1 = V_1^{\frac{3}{4}}$$

or

$$I = \frac{1}{9\pi}\sqrt{\frac{2\epsilon}{m}}\,\frac{V_1^{\frac{3}{2}}}{x_1^2}.$$

In other words, this is the largest current which it is possible to have carried by positive ions with the given distance and the given potential difference between the plates.

The value of ϵ/m for positive ions in electrostatic units is approximately 12×10^{12}.[1] If for example we take one third of an electro-

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[1] Thomson's Conduction of Electricity through Gases, p. 149.

static unit (100 volts) for the potential difference between A and C and the distance 4 cm., the current would be 2.08×10^3 electrostatic units, or 7×10^{-7} ampere. This is the amount of current which could be carried if there were only positive ions, or the amount carried by the excess of positive ions. A certain amount might be carried by negative ions, a second small amount by the positive ions which would be needed to neutralize the electrostatic effect of these negative ions and the amount given above would be the greatest possible additional amount which the excess of positive ions could carry.

The potential difference and distance assumed are similar to those existing in the experiments which have been described. The shapes of the electrodes in the experiment were indeed quite different from those considered in the mathematical treatment. But when we remember that it was possible to have an increase of nearly an ampere per sq.cm. a few centimeters away from the cathode and of many times this density of current near the cathode, we can see how improbable it is that any such increase in the current was carried by positive ions coming from the gas.

But an even more convincing reason for believing that the increase in current is not produced by a movement of the positive ions toward the cathode is given by the appearance of the luminous discharge. With non-luminous discharge there were, of course, no streams of cathode rays which could be detected. With the luminous discharge there were very noticeable cathode rays, appearing as brilliant streamers extending from the cathode to the sides of the tube or down into the gas. That these were cathode rays was shown by the effect which a magnet had upon them and by the phosphorescence which they produced. One could hardly see these streamers without realizing that something had happened to increase enormously the number of electrons leaving the cathode.

Increase in Current not due to Change in Field.—While the increase in current cannot be due to the movement of positive ions, it is conceivable that it is due to a change in field produced by them. When there is no ionization of the gas, the electrons coming from the cathode may be so numerous as to reverse the direction of the field in part of the space and hold back other electrons which may be leaving the CaO. That this actually could occur is shown by the data given in Table IV. When there are also positive ions in the field, they may so neutralize the effect of the electrons, that all the electrons which escape from within the CaO will pass to the anode. In order to consider this possibility the potential between the electrodes was examined both with non-luminous and with luminous discharge.

Potential between the Electrodes.—The apparatus shown in Fig. 2 was used to measure the potential between the electrodes, and since only one exploring wire was needed, e' was removed.

There are given in Table IV. a series of readings of the potential between A and C taken when the cathode was a dull red and a non-luminous current of 1×10^{-8} ampere was passing through the tube. In Table V. there is given a similar set taken with a luminous current of .03 ampere. In both cases the pressure of the gas was .02 mm. This was so low that there were no striations nor anode glow between the electrodes. The potential difference between A and C was 90 volts, and the distance 8 cm. Column one gives the distance from C and column two the potential difference between C and the exploring electrode as measured by an electrometer.

Table IV.

Distance from Cathode in cm.	Pd between C and e in Volts.
.3	−1.
2.	0.
4.	3.2
6.	7.7
7.	14.3

Table V.

Distance from Cathode in cm.	Pd between C and e in Volts.
.3	71
2.	71
4.	69
6.	69
7.	66

The first value in Table IV. indicates that the potential of the gas near the cathode was slightly lower than that of the cathode itself. This is due to the tendency of the CaO to give out electrons faster than the field draws them away, in fact to emit them against a small electric field, as has been pointed out by Richardson.[1]

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[1] Phil. Mag., 6, 16, 354, 1908.

In the second case the same kind of an effect occurs except that here the electric force is reversed not near the cathode but a few centimeters from it. This fact has been observed by Thomson.[1] The momentum of the ions is such that it carries them for some distance against the opposing field.

The potentials here given are much lower than those given by Westphal.[2] He was undoubtedly working with much higher temperatures than those existing in these experiments.

There results are plotted in Fig. 4, the first curve showing the potential when the discharge was non-luminous and the second when it was luminous. With the first one there is an excess of negative ions between the electrodes, with the second an excess of positive. In the first case there is little or no ionization in the gas, while in the second there is a large amount. This might at first lead one to think that the difference between these two forms of discharge was entirely due to the presence of the positive ions near the cathode and the resulting drop in potential at that point. For this would cause all of the electrons which might escape from within the CaO to pass through the tube, but further light is thrown on the matter by examining the potential between the electrodes when discharge is passing from clean platinum.

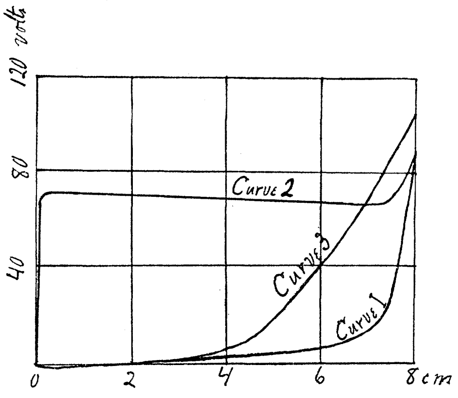

Fig. 4.

For this purpose clean platinum was substituted for that covered

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[1] Phil. Mag., 6, 18, 442, 1909.

[2] Deutsch. Phys. Gesell. Vehr., 10, 11, 401, 1908, and Science Abs., 11, p. 519.

with CaO and observations were taken with the platinum heated to a bright red. The potential difference between the electrodes was 90 volts and the current through the tube was 5×10^{-7} ampere. The potential at different points was found to be approximately the same as those given in Table IV., when there was non-luminous discharge from CaO.

Table VI.

Distance from Cathode in cm.	Pd between *C* and *e* in Volts.
.3	−1.
2	− .4
4	4.5
6	42.
7	70.

These data are plotted in curve three, Fig. 4. There is here little change between this curve and that found with small currents as far as the space near the cathode is concerned, but a large change near the anode. There is apparently ionization of the gas near the anode, but not enough positive ions are produced to change the potential of all the space.

By raising the temperature of the platinum still higher a current of 4.8×10^{-5} ampere was passed through the tube. The potential in the neighborhood of the cathode was unchanged, while that in the neighborhood of the anode was still further raised. For example, the potential 6 cm. from the cathode became 68 instead of 42 volts.

It is apparent that this form of discharge is not the same as either the non-luminous or the luminous form of discharge from CaO, since we have some ionization of the gas and yet there is no great change near the cathode. Apparently something besides ionization in the gas is needed in order to produce this change. *Some Ionization of the Gas Necessary.*—While something besides ionization of the gas appears to be necessary in order to change from the non-luminous to the luminous discharge, it is also necessary that there should be this ionization, as is shown by the following experiment.

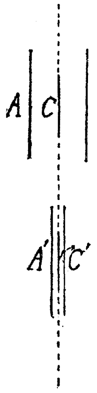

Fig. 5.

Two pieces of platinum wire, *C* and *C′* in Fig. 5, are surrounded by brass cylinders of different diameters and placed in a vacuum tube. Both wires were .5 mm. in diameter, had the same length and were heated by the same current. They were coated with CaO and were made the cathode with the cylinders as anodes. The smaller cylinder was 4.85 mm. and the larger 23 mm. in diameter. Both were 4.5 cm. in length. The potential difference between the wires and the cylinders was in all cases 90 volts. There are given in the following table the currents to the cylinders with two different pressures of the gas.

Table VII.

Pressure of Gas in mm.	Current to Small Cylinder in Amperes.	Current to Small Cylinder in Amperes.
.35	.01	8×10^{-3}
.014	5.8×10^{-6}	1.6×10^{-3}

This shows that the current to the small cylinder decreased very much when the pressure of the gas was diminished below a certain amount, and that at the same time the current to the large cylinder increased. The number of electrons coming from within the CaO was no doubt the same for both wires, and the electric force was, of course, in both cases larger for the small cylinder. In the first case the discharge to the small cylinder was the larger, as one would expect, since the electric force was larger. Apparently the small discharge to the small cylinder in the second case is due to the fact that there were then so few molecules within the cylinder that there was less opportunity for impact and consequently there was little ionization. It would, therefore, appear that while ionization of the gas is not the only requirement, it is at least a necessary requirement.

The Correct Explanation.—It has already been stated that much smaller potential differences are adequate to produce luminous discharge from hot CaO than from any cold cathode, but this is practically the only difference between the two cases. In both the luminous discharge commences with great suddenness and in both there are streams of electrons shooting out from the cathode. It would, therefore, seem as if some modification of the explanation which Thomson has given for the ordinary discharge in a vacuum would come nearer the truth than that which was suggested.

His explanation for such discharge is briefly as follows: The current through the tube is carried by ions. The production of these is a two-fold action. Negative ions which have been driven off from the cathode hit the molecules of the gas and ionize them by their impact. The positive ions thus formed are drawn up to the cathode and ionize the molecules at the surface of the cathode by their impact on them. The negative ions thus formed repeat the process by ionizing more molecules of the gas. The electric force in the tube must be sufficient to produce ionization at both of these places, but since it requires a much higher potential difference to ionize by the impact of the positive ions, it comes about that the critical potential difference is reached when such ionization begins.

It is altogether probable that the same thing occurs in the case of discharge from hot CaO, the only difference being that the molecules on the surface of the hot CaO are more easily ionized than those on the cold cathode, and there are reasons for believing that this is true, as will be given shortly.

If we make this assumption the phenomena may be explained as follows: As soon as the electric force is great enough to ionize the gas, we have a slight increase in current, such as is shown with the discharge from clean platinum. This increase does not become large, unless the positive ions thus formed are able in turn to produce ions by impact on the surface of the CaO. When this occurs, the greater the number of positive ions formed in the gas, the greater the number bombarding the cathode with the corresponding further increase in the number of electrons sent off. There is thus produced the sudden change in current which occurs at the critical point. This change is limited by the rise in potential between the electrodes which is caused by the presence of the positive ions. When this increase becomes so large that the ions are not carried to the electrode as fast as formed, the current remains stationary.

This sudden increase is probably helped by the fact that the rise in potential in the tube causes the principal drop in potential to be near the cathode, instead of near the anode. The electrons coming from the cathode have a certain velocity when first emitted. A drop in potential in its immediate neighborhood increases this and produces a greater final velocity than if applied to electrons which might be starting from rest at some point in the gas.

There are the following reasons for believing that the molecules on the surface of the cathode are more easily ionized by impact of positive ions when the cathode is hot than when cold. Due to their high temperature they are already in unstable equilibrium, as is shown by their sending out electrons even when not being bombarded. One would in fact be surprised, if it did not require a smaller momentum in this case to produce ionization than when the molecules are at a low temperature.

Secondly it has been shown by Hittorf[1] and Cunningham[2] that heating the cathode causes the cathode drop to become smaller.

Furthermore I have found that the higher the temperature of the CaO the less the cathode drop in its neighborhood. The drop given in Table V. was 71 volts, but when the temperature of the CaO was raised, this decreased rapidly. When heated as much as practical without melting the platinum foil, the cathode drop was only 8 volts.

Increasing the current through the tube also decreased the cathode drop but only to a slight extent. Thus in one case the current was varied from .02 to .4 ampere by changing the voltage at the terminals of the tube, the heating current through the foil remaining constant, and the cathode drop varied from 30 to 21 volts. The same change could be made by a very slight increase in the current heating the foil, and it is altogether probable that this change was due to the increase in the temperature at the surface of the cathode caused by the increased bombardment of the cathode and not by repeated impact on the molecules of the CaO.

Production of Electrons by Bombardment of CaO with "Canal-strahlen."—In addition to this it was shown that electrons may very easily be produced when CaO is bombarded with positive ions in the form of "canal-strahlen." It has already been shown by Austin[3] that when such rays strike a metal plate electrons are produced, but it seemed well to investigate the phenomena which exist when they strike hot CaO under conditions somewhat similar to those which held in the preceding experiments.

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[1] Wied. Ann., 21, 133, 1884.

[2] Phil. Mag., 6, 4, 684, 1902.

[3] PHYS. REV., 22, 312, 1906.

For this purpose the tube given in Fig. 6 was used. An opening was made in the side of the tube shown in Fig. 1, and a second tube, T', was sealed into this. This had a cathode, C', and an anode, A', the distance between them being 9 cm. The anode, A', was a metal disk filling the inside of the small tube and having an opening of 2 mm. in diameter in the center. A discharge could be sent through this tube by means of a Wimhurst machine or an induction coil at I and with proper pressure of the gas "canal- strahlen" would hit on the cathode, C. The anode A' was kept at the same potential as C by connecting it to the point b shown in Fig. 1.

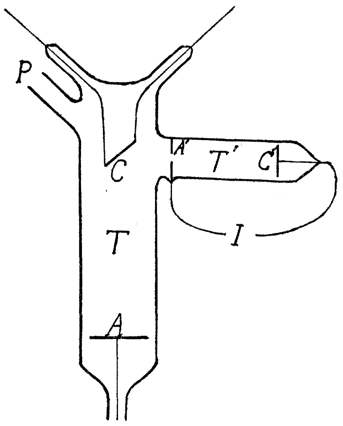

Fig. 6.

With this arrangement C was heated by passing a current through it as in the preceding experiments and a potential difference was established between A and C somewhat below that needed to cause the luminous discharge. If then a discharge was caused to pass from A' to C' so that the "canal-strahlen" hit upon C, luminous discharge would start up in T. With potential differences of about 70 volts this discharge would pass as long as C was being hit by these rays and would stop as soon as the rays would stop.

With larger voltages a continuous arc was often formed. With lower voltages the discharge between A and C was non-luminous but still considerably larger than what it was when there were no "canalstrahlen."

It was found that it was not even necessary to heat C. When C was at the room temperature, and the voltage was approximately 100 volts, the positive rays striking on C caused a luminous discharge between A and C to flash out for an instant. This luminous discharge showed striations the same as those usually produced by hot lime, and if the resistance in series with A was sufficiently small, the discharge became an arc.

Relation between this Work and the Theory of the Electric Arc.—

The work which has been described has an important bearing on the theory of the electric arc. There is no question but that the ionization at the cathode is the essential phenomenon of the arc, but there are two views concerning the cause of this ionization. According to Stark[1] and Thomson[2] the electrons are driven out of the cathode because of its high temperature in the same way as discharge is produced from hot platinum wire. The bombardment of the cathode by the positive ions heats it, but does not directly cause the ionization.

According to the other view the ionization at the cathode is produced directly by the bombardment of the positive ions on the molecules on the surface of the cathode, the same as in the Geissler tube discharge, the cathode drop in the arc being smaller than elsewhere, because a smaller potential difference is needed to produce ionization when the molecules of cathode are hot.

There are some rather serious objections to the first view. For example, mercury can be the cathode of an arc in a vacuum, although it cannot be raised to anything like a high temperature in a vacuum without changing it to a vapor. On the other hand, iron can easily be heated to a point where it will give off electrons, and yet it cannot be made the cathode of an arc in a vacuum.[3]

In addition to these arguments the work which is here described furnishes a further argument in favor of the second view. The arc is apparently the same form of discharge as that which we have been studying, for it has been shown[4] that it is possible to pass by gradual changes from the luminous discharge produced by hot CaO to that of the electric arc. The only essential difference between the two is that in the arc the current through the gas heats the cathode sufficiently to maintain the temperature of the cathode, while in the other form the temperature must be maintained by some outside source, and this difference has nothing to do with the manner in which the ions are produced.

We are, therefore, safe in saying that the weight of evidence is in favor of the view that the ionization at the cathode of the arc

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[1] Ann. d. Phys., 12, 673, 1903.

[2] Conduction of Electricity through Gases, 2d ed., p. 612.

[3] Phys. Rev., 20, 369, 1905.

[4] Phys. Rev., 29, 361, 1909.

is not caused by the high temperature of the cathode, but by the impact of positive ions on the hot surface.

Summary.—When the potential difference between the electrodes is increased the discharge in a vacuum from hot CaO passes through a critical condition, the current being very much greater after the critical point is passed and the discharge becoming luminous. It has been suggested by Sir. J. J. Thomson that this sudden change is caused by the molecules having been hit so often by the electrons that many of them are in a state of unstable equilibrium, and that when in this state but a small increase in the electric force is needed to cause ionization.

There are the following reasons for thinking that this is not the correct explanation. First, the scarcity of electrons present in the tube render such repeated collisions very improbable. Secondly, the potential difference necessary to cause this sudden change does not depend on the number of electrons passing through the tube but does depend on the condition and temperature of the cathode. Third, an examination of the potential gradient through the tube leads us to believe that the sudden increase in current is caused by something other than an increase in the ionization in the gas. Lastly the appearance of the discharge indicates very plainly that the number of electrons streaming from the cathode increases enormously when the discharge becomes luminous, becoming in fact very noticeable streams of cathode rays. On the other hand, some ionization of the gas appears to be necessary as is shown by the fact that, when the pressure of the gas is very low, the discharge from a wire coated with CaO to a small surrounding cylinder is much smaller than that to a large cylinder.

The phenomena may be explained by asssuming that ionizaton is produced at the cathode by the bombardment of its surface by positive ions and that such ionization occurs very much more easily with a very hot cathode than with one which is cold.

The potential difference between the beginning and end of a striation was found to increase as the pressure of the gas increased and to decrease slightly when the current was increased. It was in certain cases as low as 10 volts.

Because of the similarity between this form of discharge and the electric arc, it is reasonable to assume that the electrons at the cathode of the arc are also produced by bombardment of the cathode by the positive ions which come from the gas, and that they are not to any great extent emitted from within the cathode because of its high temperature. Such an explanation accounts for certain difficulties which may be raised against any other explanation.

Colgate University,
January, 1911.