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THE ABNORMAL LOW VOLTAGE ARC

By Carl Eckart and K. T. Compton

Abstract

Oscillating and stable stages of low-voltage arcs in pure helium.—Measurements with a peak voltmeter, confirmed by photographs with a Braun oscillograph, showed that with resistance in the circuit the arc went through five stages as the current was increased from 0 to 1 amp. for the tube studied; (a) voltage stable above the ionizing potential 25.4; (b) voltage oscillating from above 25.4 to below the lowest radiating potential 19.8; (c) voltage stable at practically 19.8; (d) voltage oscillating from between 20 and 24 to below 19; (e) voltage stable above 19.8. The oscillating stages were eliminated by reducing the external resistance to a low value. These phenomena are given a semi-quantitative *theoretical explanation* on the basis of a negative space charge around the filament for stages a,b,c and a positive space charge for stages d,e, and of the probabilities of excitation and ionization by electron impacts at different voltages. *Spectroscopic observations.* Lines 7065, 6678, 5876 and 5016 were relatively weak during stage c and increased in intensity with current in stages d,e.

Explanation of abnormal low-voltage arcs.—Arcs can be maintained, using a hot cathode, with an applied voltage less than the minimum critical potential in He and Hg, but not in H_2 and N_2. Such abnormal arcs are found to be oscillating, the maximum voltage in a cycle always exceeding a critical potential. The arc is maintained momentarily at a lower voltage by ionization of atoms previously excited at a higher voltage, but not in the case of gases such as H_2 and N_2, which do not exist in a metastable excited state and are not ionized by cumulative action. More recent work shows that with very intense ionization, abnormal arcs may be maintained without oscillations, because of the negative potential gradient from the anode to the boundary of the cathode drop.

I. Introduction and General Description

It has been known for some time that an arc in helium[1] and in mercury vapor[2] can be maintained at a voltage considerably lower than the lowest critical potential of the gas. The explanation of this phenomenon

[1] K. T. Compton, E. G. Lilly, and P. S. Olmstead, Phys. Rev. **4**, 282 (1920); A. C. Davies, Proc. Roy. Soc. **A 100**, 599 (1922)
[2] T. C. Hebb, Phys. Rev. **16**, 375 (1920); Y. T. Yao, Phys. Rev. **21**, 1, (1923)

has been found by Bär, v. Laue, and E. Meyer[3] and independently by the authors.[4]

The abnormal low voltage arc is a generator of alternating current, very similar to the singing arc between carbon electrodes. The apparent low voltage at which the arc maintains itself is merely the time-average of a variable voltage whose maximum value (see below) is always greater than the first radiating potential of the gas. This type of arc (in a pure gas at pressures of 4 to 6 mm) differs from the ordinary singing arc between volatile electrodes at atmospheric pressures in that no inductance or capacitance is necessary to maintain the oscillations. The period is determined by the current through the arc and by the temperature of the hot cathode. A decrease in the arc current or an increase in the filament temperature both tend to lower the pitch of the note heard in a telephone receiver.

Since the frequency is not stabilized by resonance in any circuit, it is quite variable, rendering it difficult to synchronise any other generator with the arc for purposes of measurement of frequency, etc.

II. Apparatus

The helium on which most of the experiments were made was purified by circulating over a heated mixture of copper and copper oxide, then over phosphorus pentoxide, and finally, before being admitted to the experimental tube, it passed through three traps, cooled in liquid air, two of which contained charcoal.

One charcoal trap, connecting directly to the experimental tube, and the mercury trap were kept at liquid air temperatures continuously during the time the helium was in the experimental tube.

It was found impossible to prevent the filament, which was large, from liberating traces of hydrogen, but experiments performed immediately after careful purification failed to indicate that this affected the occurrence of oscillations. This is confirmed by earlier data of Compton, Lilly, and Olmstead,[1] who used smaller filaments and thus had less difficulty in excluding hydrogen. They obtained curves which are identical in shape, to within limits of reproducibility, with the curve B of Fig. 2. It is not in agreement with the observations of Bazzoni and Lay[5] that oscillations do not occur in carefully purified helium.

During none of the work herein reported was any line of the mercury spectrum visible, nor any of the hydrogen spectrum, with the exception of $H\alpha$ which was occasionally faintly visible.

[3] Bär, v. Laue and E. Meyer, Zeits. f. Phys., **20**, 83 (1923)

[4] Eckart and Compton, Science **59**, 166 (1923)

[5] Bazzoni and Lay, Phys. Rev. **23**, 327 (1924)

The experimental tubes were of the ordinary hot cathode type. Two sizes of tungsten filament were used, one requiring 30 amp., 2.5 v., the other 16 amp., 2 v. The anode in each case was a circular nickel disk, 2-3 cm in diameter, and distant 2-10 mm from the cathode. This nickel disk was heated by an induction furnace to a red heat in order to remove adsorbed gas, principally CO.

The arc current was obtained from a 110 v. storage battery, and regulated by the usual series and parallel resistances. These were at first ordinary laboratory rheostats, 3000-4000 ohms. Later, when it became desirable to control the reactance of the circuit, they were replaced by an electrolytic resistance of approximately 600 ohms, and finally, by specially wound, non-inductive wire rheostats of 4000 ohms.

III. Experimental

(a) *Peak-voltmeter measurements on helium arcs.* The first measurements made on the oscillations were determinations of the maximum and minimum voltage attained during a cycle. These were obtained by means of a peak-voltmeter, whose operation is evident from Fig. 1.

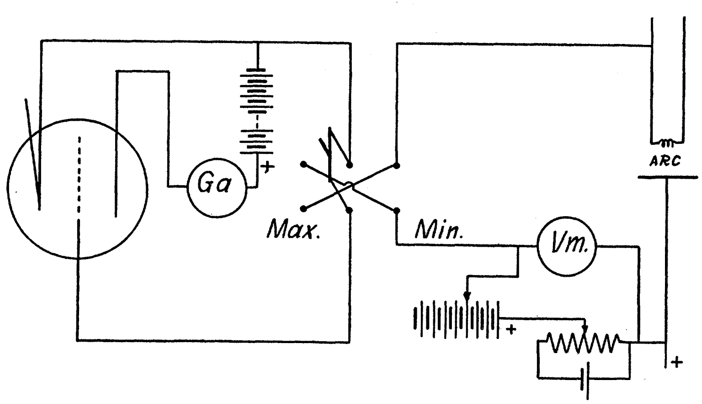


Fig. 1. Connections for determination of maximum and minimum voltages of the oscillating arc.

The results of a typical series of such measurements are shown in Fig. 2. The ordinates represent the average current, measured by a d.c. ammeter. As abscissas are plotted the minimum voltage (curve A), the average (d.c.) voltage (curve B), and the maximum voltage (curve C). The electrolytic resistance was used during the run, and the filament current obtained from local storage cells, placed on a table. The inductance of the 110 v. storage battery mains was hence the only appreciable reactance. The helium pressure was 6 mm.

Five distinct regions are apparent on these curves. First, the section *abb''* where the current is small, and perfectly steady. Second, the region *b''c*, of oscillations. The voltage here varies from a value greater than the ionizing potential (25.4 v.) to a value less than the lowest radiating potential (19.8 v.). This is followed by the region *cd*, where the arc again maintains itself without oscillations. The voltage here is almost independent of the current, and is practically at the first radiating potential.[6] Next, the region *de*, of oscillations, the voltage varying from a value greater than the first radiating potential but less than the ionizing, to a value very much less than the former. And finally, the region *ef* where the arc burns without oscillations, in the normal manner.

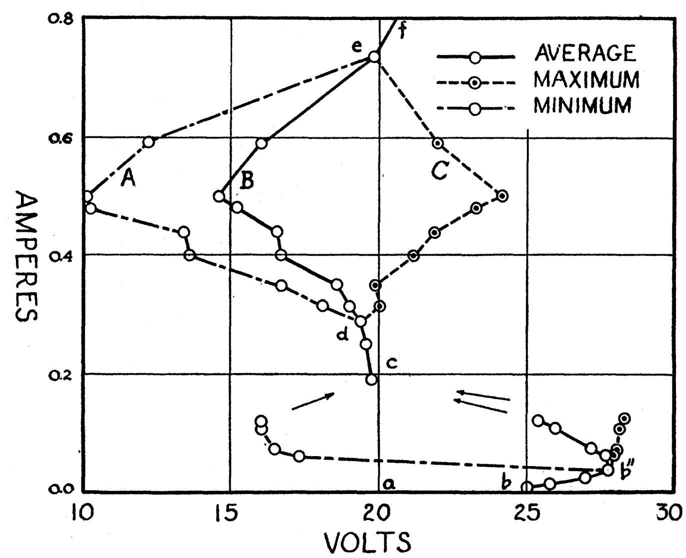


Fig. 2. Current voltage relations of arc in helium with high external resistance.

(b) *Arcs in hydrogen, nitrogen, and mercury vapor.* Observations this kind were made on arcs in hydrogen and nitrogen[7] and in mercury. In hydrogen and nitrogen, the arcs show no tendency to persist at an abnormally low voltage, and no evidence of oscillations was found. In mercury vapor, T. C. Hebb[2] and Y. T. Yao[2] have found that the arc behaves much like the helium arc. Using one of Mr. Yao's tubes, we had no difficulty in detecting the oscillations, and found again that the maximum voltage attained during the cycle was always greater than the first critical potential.

[6] All arc voltages given in this paper are *uncorrected.* The correction for filament drop is to be subtracted; for initial velocities, to be added.

[7] We are indebted to Mr. C. Kwei, of this laboratory, for the use of his apparatus for this work.

It is interesting to note that helium and mercury possess well-defined metastable states, while hydrogen and nitrogen do not. Also, collisions between molecules and electrons at velocities below the critical potentials are elastic in helium and mercury and inelastic in hydrogen and nitrogen.

(c) *Arcs with no stabilizing resistance.* Having shown that oscillations exist whenever the arc persists at an abnormally low voltage, it was desirable to show that when oscillations cannot occur, the voltage of the arc cannot drop below the radiating potential. To attain this end, the arc current was furnished by a local battery of storage cells, fitted with an end cell switch. The entire circuit, exclusive of the arc itself, had a resistance of about one ohm. Under such conditions oscillations were impossible and the current-voltage characteristic of the helium arc was similar to Fig. 3 over a range of pressures from 3 to 12 mm.

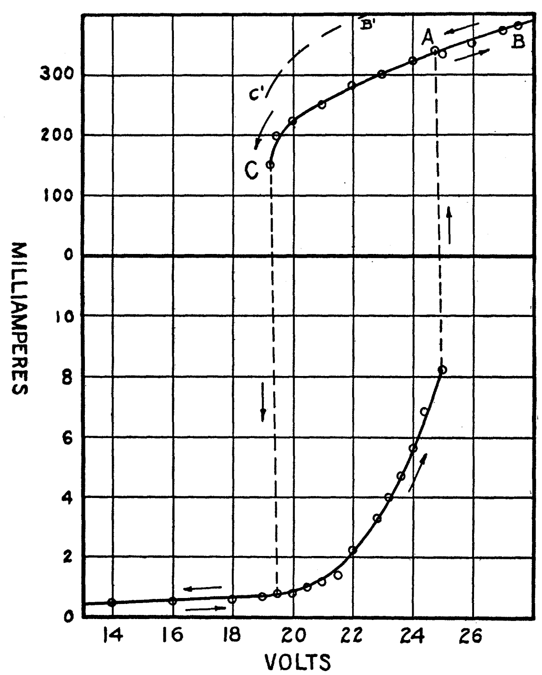
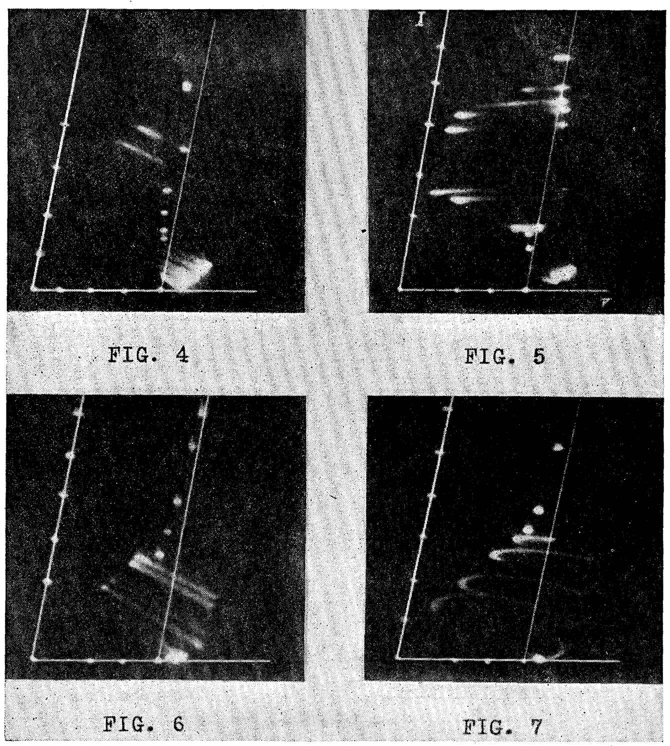


Fig. 3. Current-voltage characteristic of helium arc with very low external resistance.

(d) *Control of filament temperature.* In working with the set-up described in the previous section, it was at first thought that the curve *ABC* of Fig. 3 could not be reversibly described, that the current-voltage relation on lowering the voltage was given by the dotted curve, $B'C'$. On making the filament one arm of a Wheatstone bridge and maintaining its resistance at a constant value by regulating the heating current, this irreversibility was removed.

Similar results were obtained with the other set-up for which oscillations were possible. It was observed that no adjustment of heating current was necessary until the point *d*, Fig. 2 had been passed. This indicates that until *d* is passed, there is no appreciable bombardment of the filament by positive ions, and therefore that the potential gradient around the filament is small. This in turn means that the space charge



Current-voltage records obtained with Braun tube.

Fig. 4 is taken under the conditions of Fig. 2.
Fig. 5 shows the effect of .1 henry in series with the arc.
Fig. 6 shows the effect of 3 microfarads in parallel with the arc.
Fig. 7 shows the combined effect of inductance and capacity.

around the filament is negative throughout the whole region *abcd*. This conclusion is supported by spectroscopic evidence (see below), and has an important bearing on the theory of the arc.

(e) *Arcs with large stabilizing resistances.* It was thought that by using high series resistances and high electromotive forces, the arc might be stabilized so as to burn without oscillations in regions where otherwise oscillations would occur. By connecting non-inductive meg-ohm resistances in series-parallel, and using a 2000 v. generator or a 500 v. battery of dry cells, this was attempted. The oscillations were found to be, if anything, more stable. In one case, with 15,000 ohms series resistance, the 500 v. battery, and a low filament temperature, the oscillations started when the arc current was 2 m-amp. With lower resistance and voltage, no oscillations could be observed when the filament was at this temperature, nor, even with higher temperature, would the oscillations start until a much higher arc current (50-150 m-amp) was flowing.

(f) *Braun tube observations.* Investigation of the current-voltage relation during oscillations by means of a Braun tube confirmed the previous results. Figs. 4, 5, 6, and 7 are photographic records of the position of the luminous spot of the Braun tube for various settings of the control resistances. The ordinates represent current, the abscissas voltage. The lighter line parallel to the current axis is drawn through 20 v., i.e., approximately the lowest radiating potential.

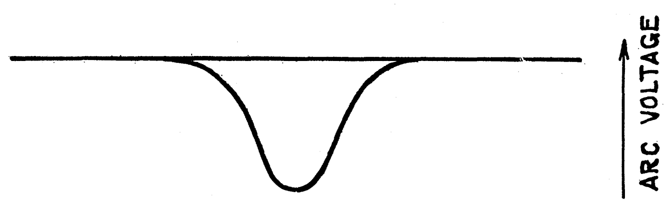


Fig. 8

Fig. 4 was taken under the conditions of Fig. 2 and shows the regions of oscillation distinctly. The relative blackening of various parts of the lines indicating oscillations is interesting. The low current, high voltage (22-27 v. max.) type of oscillation shows most intense blackening near the maximum of voltage. Blackening being roughly inversely proportional to the velocity of the spot, this shows that the voltage remains at its maximum for a considerable length of time compared to the interval during which it passes through the lower values. The oscillations are hence rather a series of brief surges of current, with accompanying potential drop, than true oscillations.

This was confirmed by impressing an alternating voltage of sine form across the horizontal deflecting plates of the Braun tube, and the arc voltage across the vertical plates. While it was impossible to photograph the resulting curves, or even to keep them sufficiently steady for convenient visual observation, their general shape is shown in Fig. 8. The high current, low voltage type could not be examined by this method at all, owing to its irregularity in the absence of reactance.

Fig. 5 shows the marked increase in the amplitude of voltage variation and reduction of current variation which results from 0.1 henry inductance in series with the arc. Fig. 6 shows the effect of 3 microfarads in parallel with the arc, and Fig. 7 the combined effect of inductance and capacitance.

(g) *Spectroscopic observations.* Some observations made on the spectrum of the arc in helium are of importance in the formulation of a theory of the arc. They are, however, to be regarded merely as preliminary results.

Of the purity of the helium used in these experiments there can be no question. As mentioned above, $H\alpha$ was the only line corresponding to impurities which was ever observed while working; but during this work it was not visible. The helium band at λ 6400 was visible, and our experience has been that it is rarely visible simultaneously with $H\alpha$.

The four lines 7065 $(1\pi-2\sigma)$, 6678 $(1P-2D)$, 5876 $(1\pi-2\delta)$, and 5016 $(1S-2P)$ were observed visually while the arc passed through its various stages. The instrument used was a Hilger constant deviation wavelength spectrometer. The helium pressure was 5 mm. It may be noted that the conditions of this work are not comparable with the conditions under which some recent work on the spectrum of helium was done,[8] for the electron bombardment was very much more intense in our work than in the other.

All four lines appeared, apparently simultaneously, between the states b and b'' (Fig. 2). They were first visible near the anode, and, as the arc passed through the various states of oscillation $b''c$ they lengthened out. In the region cd, they first suffered a marked decrease in intensity, then increased again. During this increase, the position of maximum intensity shifted toward the cathode from a point midway between anode and cathode. The maximum intensity of the lines reached the cathode when the arc reached the state d; this is also the point at which the ionic bombardment begins. Throughout the region def, the lines increase uniformly in intensity.

IV. Interpretation of Results

Although it has not been possible to formulate a complete quantitative theory of these oscillations, the following semi-quantitative treatment seems to be a fairly satisfactory physical interpretation of the phenomena.

There are two conditions which must be satisfied by the arc current and voltage. The one is imposed by the external electrical circuit, and

[8] Udden and Jacobsen, Phys. Rev. **23**, 322 (1924);
Bazzoni and Lay, Phys. Rev. **23**, 327 (1924)

the other by the internal characteristics of the tube. The former is very simple, but the latter is complex.

Consider the simplest possible circuit (Fig. 9) containing the discharge tube, a constant non-inductive resistance R, and a variable electromotive force E, all in series. Then, for any given electromotive force E, the current i and the voltage drop across the tube, V must satisfy the relation

$$V = E - Ri\ . \tag{1}$$

In the graph of Fig. 9, the line DE is the graph of this equation for the value of E given by OE. Its slope is $-1/R$, and is therefore steeper the

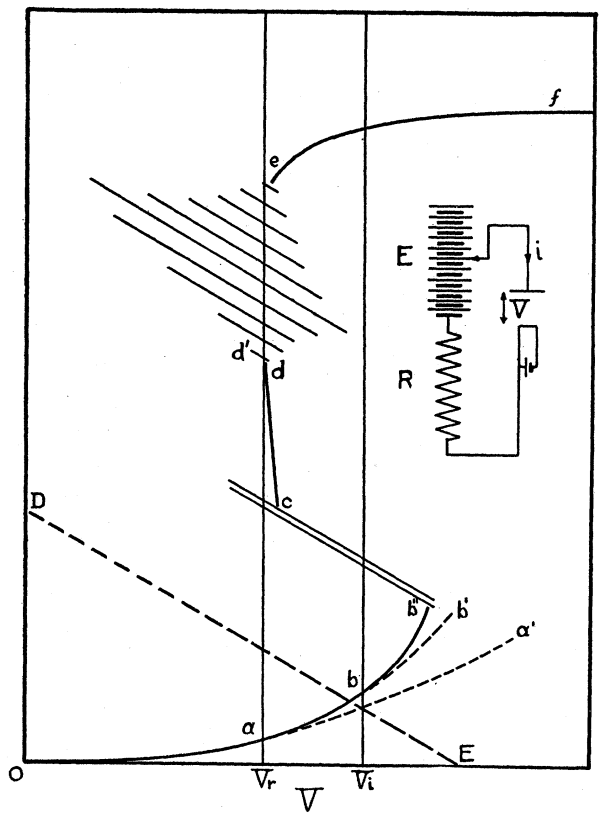


Fig. 9. Theoretical current-voltage curves.

smaller R. If E is increased, Eq. (1) determines another line, parallel to DE, and to its right.

The external conditions require, therefore, that the point representing the actual values of i and V shall lie on this line. The particular position on the line depends on the second condition.

The internal conditions can most conveniently be studied in six successive stages, corresponding to the various regions *ab*, etc., of Figs. 2 and 9.

(a) *Stage oa.* $V < V_r$. If the potential drop V is less than the lowest radiating potential V_r, there can be no ionization of the gas, and the current is limited by negative space charge to a value given by

$$i = CV^{3/2}, \tag{2}$$

where C is a constant depending on the geometry of the tube, the value of e/m for electrons, and the ratio of the electronic mean free path to the distance between cathode and anode.[9] Equations (1) and (2) determine uniquely the value of the current, which does not exceed a few microamperes. Were it not for ionization at higher vo tages, the current would continue to be determined by these equations, and the current voltage curve would extend along *oaa′*.

(b) *Stage ab.* $V_r < V < V_i$. When the voltage exceeds the minimum radiating potential but is less than the minimum ionizing potential V_i, ionization is possible by cumulative action; i.e., electrons may ionize at impact atoms which are already in an excited state as the direct or indirect result of previous impacts.[10] This ionization is important, not so much because of its direct contribution to the current as because the positive ions thus formed neutralize the negative space charge and permit the escape of additional electrons from the filament. Each positive helium ion thus liberates several hundred additional electrons between the time it is formed and the time it is neutralized at the cathode. The exact number depends on the relative mobilities of electrons and positive ions. The effect of ionization is thus magnified, and causes the current to exceed the value it would have in the absence of ionization, as is shown by the curve *abb′*.

The nature of this curve may be indicated by the following analysis, which is a refinement of a less accurate treatment previously published.[11]

Consider an applied potential V, a little greater than V_r, and let N_0, as given by Eq. (2), be the number of electrons that would escape per second from the filament if there were no ionization. These may make effective impacts only in a layer of gas near the anode, of thickness proportional to $(V - V_r)/V$. Some of these collisions produce excited atoms and, if their number is not too great, we may say that the fraction of the atoms in this region which exist in an excited state is proportional to the number

[9] Langmuir, Phys. Rev. **21,** 419 (1923);
Richardson and Bazzoni, Phil. Mag. **32,** 426 (1916)

[10] K. T. Compton, Phys. Rev. **20,** 283 (1922); Phil. Mag. **45,** 750 (1922)

[11] K. T. Compton, Phys. Rev. **20,** 283 (1922)

n of electrons traversing it. Call this fraction Pn, where P is the fraction which would exist in the excited state if the current were one electron per second. If N is the number of atoms in this layer, then the number of excited atoms is PNn. Some of these excited atoms will be ionized by another impact. Since this ionization is jointly proportional to the number of excited atoms and to the number of impacting electrons, we can put this cumulative ionization equal to $I_c = APNn^2$, where the constant of proportionality A involves the probability of colliding within the region and of ionizing an excited atom at a collision. If each positive ion liberates M additional electrons from the filament, there are added to the current $MI_c = MAPNn^2$ electrons. But some of these will also produce excited atoms and ionize them, and thus add still further to the current, etc.

Starting with n_o original electrons, we have as a first approximation to the total number

$$n_1 = n_0(1+kn_0)\ , \quad \text{where} \quad k = MAPN\ .$$

As second and third approximations we have

$$n_2 = n_0 + kn_1 \quad \text{and} \quad n_3 = n_0 + kn_2\ , \text{etc}\ .$$

Proceeding thus, and reducing, we find, in the limit,

$$n = n_0(1+kn_0+2k^2n_0^2+5k^3n_0^3+14k^4n_0^4+42k^5n_0^5+\cdots)$$

which may be written

$$n = \frac{n_0}{1-kn_0}\left[1+\frac{k^2n_0^2}{(1-kn_0)^4}(1+3k^2n_0^2+21k^3n_0^3+\cdots)\right]. \tag{3}$$

This series is convergent for small values of kn_0 but rapidly approaches infinity if kn_0 becomes comparable with unity. Since we are dealing at present with very small values of kn_0, we may consider only the first part of equation (3) as a close approximation.

In the equation $n = n_0/(1-kn_0)$ something can be said about the dependence of k upon the voltage V. In $k = MAPN$, we have P depending on the probability of excitation at impact, which is believed to be maximum at $V = V_r$ and to decrease with increasing voltage. We shall probably have something like the right type of relation if we put $P \propto (V_r/V)^s$, where s is some undetermined exponent. N is proportional to the thickness of the region in which excited atoms are formed, hence to $(V-V_r)/V$. A is proportional to $(V-V_r)/V$ and also to the probability of ionization of excited atoms by impacts of energy V, which probably is nearly constant within the range involved since this range is several times higher than the critical energy required, about 5 volts. Thus

$k=C(V-V_r)^2/V^{s+2}$ should represent crudely the way in which k depends upon V. We have, therefore, as a rough approximation

$$i = \frac{i_0}{1-Ci_0(V-V_r)^2/V^{s+2}}, \tag{4}$$

where $i=ne$, $i_0=n_0e$.

Eq. (1), (2) and (4) uniquely determine the currents for values of V not greatly in excess of V_r, and are experimentally found to show the right sort of relation between i and V in the region *ab* of the curve.

If i_0 is large or if the apparatus is so constructed as to make C large, the denominator of Eq. (4) may become zero, making the current infinite, at a value of V less than the minimum ionizing potential V_i. This simply means that the current takes the saturation value determined by the temperature of the filament. But the external condition expressed by Eq. (1) may introduce complications discussed below in stage (e). Usually, however, the current is still small by the time the voltage has been increased to the ionizing potential V_i, at which point another factor must be taken into account, as follows.

(c) *Stage bc; first region of instability.* $V>V_i$. When the voltage V exceeds the ionizing potential V_i, ionization of normal atoms by single impact as well as cumulative ionization may occur. The probabilities of these two types of ionization vary with the voltage in different ways so as to produce a condition of instability causing the voltage V to decrease discontinuously if the electromotive force E is increased above a certain point.

The amount of cumulative ionization I_c is proportional to the square of the total current i, since the probabilities of excitation and of subsequent ionization are both proportional to the current. These probabilities are also functions of voltage, $F(V)$ and $F'(V)$ respectively. Thus we may put $I_c=CF(V)F'(V)i^2$, where C is independent of V and i. Similarly the amount of ionization I_d by direct impact is proportional to the current and to the probability $f(V)$ of such ionization by an impact at voltage V. Thus $I_d=Df(V)i$, and the total ionization may be written

$$I=Df(V)i+CF(V)F'(V)i^2\,. \tag{5}$$

The forms of these functions are not known accurately, but we know that $F(V)$ decreases as V is increased above V_r, $F'(V)$ is about constant in this region, which is considerably above the critical value of about 5 volts, and $f(V)$ increases as V is increased above V_i. It is evident that I will increase as V increases up to a certain value of V, above which I and i take their maximum values when V decreases to V_r. This may be shown thus:

Assume, as an approximation, $F(V)=(V_r/V)^s$; $F'(V)=\text{constant}$; $f(V)=(V-V_i)/V$. Then

$$I=D\frac{V-V_i}{V}i+C\left(\frac{V_r}{V}\right)^s i^2 . \qquad (6)$$

Combining this with equation (1) to eliminate V, we find a relation between I and i for any value of E. Furthermore, I and i must also be related by an equation

$$i=i_0+MI , \qquad (7)$$

as discussed in the preceding section. Combining equations (6) and (7), it is found that, for small values of E, there is only one possible value of current i, and the voltage V exceeds V_i. At higher values of E two possible solutions are found, one in which the voltage V exceeds V_i and the other in which the current i is larger and V is but slightly in excess of V_r. Presumably the solution with the larger current represents the stable condition, since it leads to the maximum dissipation of heat in the system. These results may easily be verified by graphical solution of the equations. The detailed analysis is not presented since the assumptions are not quantitatively accurate; the important point to be noted is that any forms of the functions F, F' and f which are consistent with our present knowledge lead to the general conclusion just stated.

Thus we see that, as E is increased, i and V both increase beyond the point b until a certain stage is reached at which the voltage suddenly drops to a value close to the radiating potential V_r, with a simultaneous increase in current.

This analysis points out a reason for a discontinuity between b and c, but it does not show any cause for sustained oscillations. This is consistent with experimental observations to the effect that oscillations in the region of this discontinuity tend to vanish as care is taken to insure steadiness in the tube and circuits and to reduce inductance and capacity to a minimum. Under ideal conditions we believe this to be a point of discontinuity in the current-voltage relation, with no oscillations. A little inductance, however, causes oscillations to occur.

(d) *Stage cd. V constant at V_r.* As E is still further increased, the current rises with a practically constant voltage of 20 volts, or V_r. This continues for a range depending on the temperature of the filament. In one extreme case with a very hot filament the range *cd* involved an increase in current to 40,000 times its value at *c*.

During the entire range *oabcd* the filament has been surrounded by a negative space charge. We believe this to be proven by the observations on the heating of the filament by bombardment, and by the manner in which the spectral lines vary in intensity, as pointed out earlier in the paper.

We can thus attribute all increase in current up to the point d on the curve as due to neutralization of negative space charge by positive ions, permitting the escape of more electrons. By this process the space charge still remains negative so long as the potential supply of electrons is large, i.e., if the current is well below the saturation current determined by the temperature of the filament. As this is approached, however, not every incoming positive ion finds its corresponding number of electrons awaiting release, and the space charge becomes less negative until, at some value of the current, it changes sign to positive. We believe that the point d marks this change.

(e) *Stage de; oscillations about* V_r. As pointed out above, the sign of the space charge around the filament is positive in this region, which means that the filament is surrounded by a field tending to draw away electrons. There is nothing, therefore, to prevent the current from immediately attaining its saturation value. But no change can occur except along a line parallel to DE, determined by the series resistance. Thus the current and voltage tend to change as shown by the line dd'. But this takes the voltage below V_r, so that the current can only persist as long as there remains in the tube a sufficient number of excited atoms to permit the necessary ionization. When this number becomes insufficient the current diminishes and the voltage increases again to a value above V_r, and the cycle is again repeated.

Besides the apparent logical necessity for such an explanation of the oscillations, there are three considerations which support it. Such oscillations have been observed in mercury and helium, both of which may exist in metastable and excited states, but not in hydrogen or nitrogen, which do not. The period of the oscillations is of the order of a thousandth of a second, which is the order of magnitude of the life of the metastable atoms.[12] Also the minimum voltage attained during the oscillations was frequently found to be close to 5 volts, but never appreciably less. Since about 5 volts represents the minimum energy necessary to ionize excited atoms, we again have support for the explanation offered above.

(f) *Stage ef; saturation current.* $V > V_r$. The oscillations cease when the electromotive force E is so large that the external condition of equa-

[12] Kannenstine, Astrophys. Jour. **55**, 345 (1922). In this paper is noted an observation of oscillations, apparently the first in the literature of the subject. The conditions of the experiment were, however, not such as to permit the cause or significance of these oscillations to be recognized.

tion (1) can be satisfied by the saturation current i_s with a value of V greater than V_r. Unless precautions are taken to maintain the filament at constant temperature, the current rapidly rises with increasing E owing to the increasing temperature caused by positive ion bombardment. With the Wheatstone's bridge control of temperature mentioned above, this part of the curve was much more nearly horizontal, but not entirely so. This is probably due to the fact that the thermionic current from the filament disturbs slightly the balance of the bridge, behaving like a leakage. We did not attempt to compensate for this effect, which can be done.[13] We are informed by Dr. Langmuir that the saturation current from a hot filament in this sort of discharge in an ionized gas is always found to be constant if the temperature is controlled by the more accurate means of an optical pyrometer.

Special cases. Finally, it may be remarked that experimental conditions may be such as to suppress certain of the stages mentioned above, or to modify the action.

If the series resistance R is sufficiently small, the slope of the line DE may be so increased as to cause the point c to fall above the point d, in which case the stage cd is not present. If R is so small that the discontinuous change from b'' to c is such as to cause the line $b''c$ to intersect the line ef, the voltage V at the break does not fall below V_r and the oscillations, or interruptions, of the current do not occur. There is then a large discontinuous current increase—the phenomenon usually called the "striking of the arc."

If the tube is so constructed as to give a large value to the current as limited by space charge without ionization, then the "strike," or break from a point on the curve abb'' to a lower voltage and higher current may occur at some point between a and b, as shown by Eq. (4) when i_0 is large. The particular stage to which the current passes depends, as before, on the value of the series resistance. A small filament, close spacing of electrodes and a pressure of 1 to 4 mm are favorable for such a transition.

Finally the oscillations of stage de may set in at any lower part of the curve if the saturation current i_s is reduced and the series resistance high. In fact the point d at which they set in seems to be when the current i reaches a value about equal to $(2/3)i_s$, whatever is the value of i_s. This is an additional support of the explanation of the oscillations which we suggest, since it is what we should expect if the point d comes when the supply of electrons held in by space charge can no longer be regarded as

[13] Cooke and Richardson, Phil. Mag. **25**, 624 (1913)

inexhaustible. In this way these oscillations may set in even below the point b'' on the curve, although not without high series resistance since otherwise the slope of the transition curve $b''c$ would be so steep as to cause the current to reach the saturation value without a drop in voltage below V_r.

In conclusion the authors wish to express their appreciation to the Edison Lamp Works of the General Electric Company, for their support of this research by a fellowship and by furnishing some of the material used in constructing the apparatus.

Note added July 14. Since writing the above paper we have discovered that, with ***very intense ionization***, the arc may be maintained *without oscillations* at a voltage distinctly below the lowest critical potential of helium and mercury and far below it in argon. This we have proved to be due to the negative potential gradient from the anode to the boundary of the cathode drop. The cathode drop is never less than the critical potential of the gas. A preliminary note on these results has been sent to Nature and the complete report will be published in due course.

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PRINCETON, NEW JERSEY.
April 11, 1924.

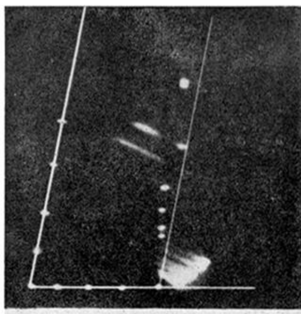

FIG. 4

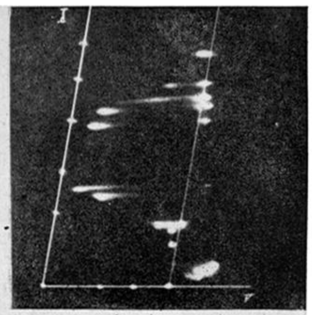

FIG. 5

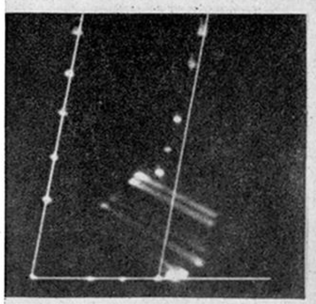

FIG. 6

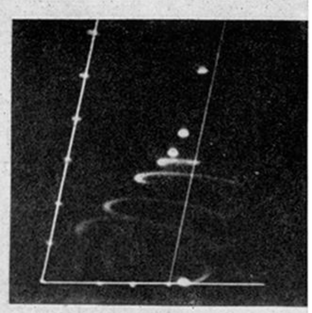

FIG. 7

Current-voltage records obtained with Braun tube.

Fig. 4 is taken under the conditions of Fig. 2.
Fig. 5 shows the effect of .1 henry in series with the arc.
Fig. 6 shows the effect of 3 microfarads in parallel with the arc.
Fig. 7 shows the combined effect of inductance and capacity.