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The Role of the Cathode in Discharge Instability*

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It is shown that a highly stressed conditioned cathode in a gas will, by positive space charge action, produce an autocatalytic increase in current through a chain reaction leading to complete breakdown. Depending on conditions in the circuit this common tendency will explain a number of phenomena. In pure free electron gases, the discharge has a negative characteristic and must be controlled by external resistance or else lead to an arc. In the presence of adequate low field regions and moderate negative ion formation, a current controlled by the internal space charge resistance of the system results. Where negative ion formation is heavy and low field regions exist, the discharge will choke itself off and be intermittent. In cases where there are large electrically elastic columns of ionized gas at lower pressure that can be swept by ionizing potential waves, as in glow discharges, the cathode instability leads to pulsations or moving striations and is the cause of setting up and sustaining plasma oscillations. Among the consequences of such action where intermittent or pulsed discharges occur, there will be a Faraday dark space and perhaps striations. Faraday dark spaces will occur only where cathode instabilities cause current fluctuations and should not be observed in more stable discharges.

THE circumstance that in relatively high fields the negative carriers are mobile free electrons, while the positive carriers are the more sluggish gaseous ions, leads inevitably to conditions which can make the cathode region a source of instability in many gaseous discharges. Such instabilities now appear to be much more common than heretofore suspected. They manifest themselves in peculiar phenomena whose nature and common origin have remained obscure. Thus, for instance, one would hardly suspect that the following phenomena had a common origin, to wit: (a) the equality of onset thresholds of some positive and negative coronas, (b) the breakdown of some gaps directly to power arcs, (c) the transitions from Townsend discharge to glow discharges, (d) the transitions of some glow discharges to power arcs, (e) the negative resistance characteristics of many arcs and some corona discharges, (f) the appearance of periodically interrupted pulsed coronas, (g) the existence of the Faraday dark space and the appearance of striations in some otherwise seemingly, steady direct current discharges, (h) the appearance of sustained plasma oscillations of a wide range of frequency from megacycles to microwave frequencies in some discharge tubes.

It is the purpose of this paper to indicate a basic common origin and to associate it with the asymmetry of carrier nature and cathode function. If one regards a highly stressed region near the *anode* of an electrode system at a pressure leading to ionization by electron impact, it will be noted that the electrons and electron avalanches of $e^{\int \alpha dx}$ electrons created by Townsend ionization in the high field regions converge toward the anode. The ionization increases exponentially as the electrons approach the anode. The electrons reaching the anode are relatively rapidly absorbed, leaving behind a space charge of positive ions moving relatively slowly outward. Especially at higher pressures, with the proper geometrical field conditions, in gases having a high absorption coefficient and capable of photo-ionization by high energy photons created by the avalanches, a self-propagating discharge streamer sometimes leading to breakdown can materialize. In, however, a large variety of conditions near the threshold, this action is not possible. The net result of the ionization by converging avalanches is the creation of an outwardly moving positive space charge near the anode, which will in greater or lesser degree control the discharge current by acting as an internal space charge limiting resistor. In some discharge regions such as corona just above onset, space charges will even choke off the discharge as in the Geiger counter regime. Thus, while under some extreme conditions and primarily at higher potentials, a breakdown can initiate as a streamer from the anode, in a majority of cases the removal of electrons leaves behind a positive space charge which acts to limit and control the current, thus preventing transition and breakdown until much higher potentials are reached.

The situation with the negative electrode is quite the opposite, as will readily be seen in what follows. Electrons leaving the highly stressed cathode surface at appropriate pressures will move outward from the cathode ionizing cumulatively as they leave the cathode. In so doing, they soon reach regions of lower field strength where the rate of ionization rapidly falls off owing to the decreased field and consequent rapidly decreasing value of Townsend's first coefficient α. Thus, despite the exponential increase of electrons in the avalanches, the rate of ionization rapidly declines to inappreciable values. The electrons of high mobility leave behind a distribution of positive ions which, sparse near the cathode, increases to a peak at some distance from the cathode, and decreases to a very few at the point where the rate of electron ionization has fallen to negligible dimensions. This positive ion space charge converges on the cathode. In doing so it acts to

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augment the field next to the cathode surface in a measure consistent with its density. These space charges can thus act only to augment the field near the cathode and thus enhance the ionization of subsequent electron avalanches. That is, cathode action has inherent in itself a potentially autocatalytic character. Under proper conditions, such action can lead to a chain reaction and catastropic breakdown. The cathode is thus a potential source of instability.

The realization of this instability involves secondary ionizing processes which are especially propitious at the cathode in the lower pressure ranges. For photons created by the avalanches reaching the cathode can liberate photoelectrons from the *metal surfaces* in much greater quantity than is the case for the *photoelectric ionization of the gas* by photons in the neighborhood of the anode. Furthermore, at higher fields, the positive ions whose ionizing potential is above the work function of the surface can liberate electrons from it by positive ion impact. Their efficiency increases rapidly with the field strength. If now the condition of the surface is such that the primary avalanches of $n_0e^{\int\alpha dx}$ electrons can create enough positive ions and photons effectively to augment the incoming positive ion space charge, the basis for the initiation of a catastrophic chain reaction is at hand. Such action once it starts is enhanced by still another effect. In general, fields at the cathode surface are fairly high when breakdown at cathodes starts. Appropriate positive ion densities approaching the surface can increase these fields by an order of magnitude or more. If these fields reach appropriate magnitudes, the ordinary Townsend ionization, represented by the coefficient α, and the use of the expression $e^{\int\alpha dx}$ is no longer valid. In such electrical fields the electrons cease to remain in equilibrium with the field as Townsend's mechanism requires. Thus, the Townsend ionization is replaced by the more efficient Morton-Johnson[1] ionization processes. The primary ionization function is therefore replaced by functions which may be greater by a factor of several hundred percent as observed by Morton and Johnson. This further augments the density of positive ion space charge and further increases the rate of the chain reaction. Thus, there is present with any given cathode and gas a potential instability of considerable effectiveness.

Whether such instability develops in a given combination of electrodes fields, pressure, and gases depends critically on the condition of the cathode surface, the positive ion types, and the electrical fields. Too little is known today about the secondary electron liberation, especially by positive ion bombardment to permit one to be specific. The secondary emission by photoelectric ionization at the cathode is always present for metal surfaces, but it is questionable whether by its magnitude it alone can yield the autocatalytic breakdown described above. It is, however, very likely from the data yielded by recent observations[2,3] that at appropriately high fields the field intensified currents, i.e., $n_0e^{\int\alpha dx}$, yielded by n_0 externally produced electrons from the cathode will evolve into a self-sustaining Townsend discharge. This will set in with potentials and fields at the cathode satisfying the condition $\eta\theta g/\alpha e^{\int\alpha dx}=1$. Here η is the number of active photons produced per electron in the avalanche, g is a geometrical factor determining what fraction of these reach the cathode, and θ is the chance that these will lead to the emission of a secondary electron. The resulting avalanches produce enough positive ions to render the discharge self-sustaining. It is inadequate to yield the positive ion space charge leading to the chain reaction and indefinite increase in current is controlled by negative space charge resistance in the low field regions. Such currents will rapidly increase with potential largely owing to the increase of $\int\alpha dx$. They still may not produce enough positive ions to yield an adequate space charge effect.

Now the high fields at the cathode are such that above the threshold in many discharges the positive ions striking the cathode have been observed to sputter or blast atoms of the cathode from the surface.[4] At the lower fields existing in the Townsend discharge region, these same ions are certainly capable of cleaning the cathode surfaces of oxide and of gas films. If oxygen or chemically active gases are present, these gases will strive to reform the films by diffusion. Such films are known to alter and frequently to increase the work function of the pure metal surface.[5] Increased work function or other action will lower both θ and the γ for secondary electron liberation by positive ion bombardment. If then, as the potential of the cathode is made more negative, the Townsend discharge current reaches such a density of positive ion bombardment as with adequate duration to clean up the surface, the cathode will end up as a clean surface. It will thus reach a condition of low work function and high θ or γ. On the appearance of high secondary emission, the chain reaction can set in and the condition of instability is achieved. A cathode under such circumstances will find itself highly "overvolted," since γ and θ can increase by an order of magnitude or more on the clean surface. The achievement of such clean-up by the low order Townsend discharge initiated on a dirty surface by photoelectric action and possibly by a γ of low value, will depend on a number of factors. These are the nature of the surface, its initial condition, the nature and pressure of contaminating gas present, and the geometry of the field affecting the current density of positive ion bombardment and its energy of bombardment. All these factors have been observed to determine

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[1] P. L. Morton, Phys. Rev. **70**, 358 (1946); G. W. Johnson, Phys. Rev. **73**, 284 (1948).

[2] W. N. English and L. B. Loeb, J. App. Phys. **20**, 707 (1949).

[3] Charles G. Miller, Ph.D. Thesis, University of California, 1949.

[4] Hudson, Loeb, Bennett, and Kip, Phys. Rev. **60**, 714 (1941).

[5] G. L. Weissler and R. W. Kotter, Phys. Rev. **73**, 538 (1948).

the nature and clean-up of the surface in the course of recent studies.[2,3] Once the potential of the cathode is such as to produce the clean surface, then the threshold of the appearance of one of the many possible phenomena to be expected with the overvolted clean surface and the attendant chain reaction can be expected.

The manifestations possible with such a surface are varied and may now be listed and discussed.

1. If the gas is very pure and of a type that does not attach electrons and form negative ions, it is to be expected that clean-up will follow in time, depending on the initial soiling of the cathode surface, once the threshold of the low order Townsend discharge is reached. Thus, breakdown and Townsend threshold occur at nearly the same potential. Breakdown will be far more rapid the higher the potential above the Townsend threshold, as then the increased value of $e^{\int \alpha dx}$ will produce more intense bombardment and more rapid clean-up. Once the surface is clean, the chain reaction sets in and the breakdown develops into a power arc, unless there is a current limiting resistor in the outer circuit. If the gap has a long low field region and the gas is clean, there is a chance that the electron space charge in the low field regions may act to limit the discharge. Transitions from a Townsend discharge to an electron space charge limited current 1000-fold greater at constant potential have been observed by G. L. Weissler[6] in negative point corona in pure N_2 and H_2. With shorter gaps, C. G. Miller,[3] with N_2 and H_2 in a concentric cylindrical corona gap found that the discharge went to arc over unless he used an external limiting resistor. Here the currents jumped from 10^{-10} ampere on clean-up to 10^{-2} ampere or more.

2. If gases like O_2 are present in the N_2, then negative ion formation with oxides of nitrogen, O_2 molecules, and O atoms takes place. Under these conditions, the enormous burst of electrons from the chain reaction builds up such a heavy space charge of slowly moving *negative* ions in the lower field regions as to reduce the fields at the cathode to values where cumulative ionization is no longer possible.[7] The discharge then terminates until the space charge of negative ions is cleared by the field when a new discharge can start. The discharge is, therefore, an interrupted discharge of the Trichel pulse type. The magnitude and duration of the pulses depend on the rate of negative ion formation and electron liberation. In such cases the negative pulse onset, or "breakdown," is higher in negative potential than the Townsend threshold as the larger Townsend current is needed to clean up the surface.[2] The pulse onset is lower the higher and the more convergent the field at the cathode and the lower the pressure of O_2.

3. In such discharges the maximum luminosity occurs at the height of the pulse. The enormous burst of ionization liberates electrons so rapidly compared to their removal in the lower field region, that even before much attachment to ions has occurred, the discharge will show not only a Crookes dark space and a negative glow but a Faraday dark space as well. In the stationary low order Townsend discharge, calculation of the rate of ionization would lead one to infer only the presence of the Crooke's dark space and the negative glow. Thus, it seems likely that the appearance of the Faraday dark space in discharges is not a property of the steady Townsend discharge. Instead it is caused by a transient, unstable regime where overproduction of electrons in one phase produces a second region of high potential gradient beyond the negative glow. This is a condition in which the electrons pile up so heavily in the low field region as to possibly hold back positive ions and to produce a steep gradient with the outward lying more positive portions of the discharge. This has recently been strikingly confirmed by observations by H. W. Bandel[8] that for large points and lower pressures the intermittent Trichel pulses give way through a fluctuating corona to a steady direct current discharge of higher value. The higher potentials, broader fields, and low pressures prevented the choking action of the negative space charge by reducing attachment, thus terminating Trichel pulses. When this occurs the Faraday dark space disappears and the positive column becomes diffuse and general, shading into the negative glow.

4. It is possible that the intense electron liberation leading to enormous current increase will be accompanied by a compressive effect on the cathode regions of the discharge.[7] Such compression results from the distortion of the equipotential surfaces between regions of discharge along the axis and the surrounding regions of no discharge. This so concentrates the current that the current densities observed in the low boiling point metal vapor arcs of in excess of 10^5 amperes per cm^2 are achieved. Under such conditions the intense local surface heating leads to a disruption of the surface in the form of vapor jets. It begins to be assumed that such jets in part cause the peculiar wandering of the cathode spots in these arcs. This action constitutes a different type of disturbance of the discharge, to wit, by a destruction of the surface also owing to the chain reaction. It in turn also acts to limit the discharge. Actually both in coronas and arcs such confined discharges are able to carry only a limited current. Thus, increased current resulting from lowered external resistance is achieved only by the appearance of multiple spots as has been observed in corona studies and in Hg arcs by Froome.[9] Incidentally, it appears that in arcs where the current is controlled by external resistors, one does not have the pulsating instability resulting from the overproduction of electrons. Thus so far only the Crookes dark space and negative glow have been observed in arcs. The Faraday dark space is absent.

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[6] G. L. Weissler, Phys. Rev. **63**, 96 (1943).

[7] L. B. Loeb, J. App. Phys. **19**, 882 (1948).

[8] H. W. Bandel, work currently in progress, University of California.

[9] K.D. Froome, Proc. Phys. Soc. London **60**, 424 (1948).

5. Under appropriate conditions of low pressure together with an extensive gaseous path length yielding a high controlling internal resistance, one has the glow discharge. With a steadily applied potential, these discharges appear to the eye to be thoroughly stable, steady discharges. They have a positive resistance characteristic. They show a Crookes dark space, a negative glow, and a Faraday dark space. In some cases the Faraday dark space is followed by other dark spaces in the striated discharge with stationary striations. Until very recently such discharges have been assumed to be stable and steady. To the writer at least there was no satisfactory explanation of the reason for the appearance of the Faraday dark space or striations which appeared as some sort of standing potential wave pattern. Very recently G. H. Dieke and T. Donahue[10] have studied the steady glow discharge by means of a photomultiplier tube and oscilloscope. These studies revealed that what to the eye appears as a *steady glow* is in reality a seething mass of pulsations of a most complicated form. Negative striations initiate near the negative glow and travel toward the anode. Positive striations start from the anode region and move towards the cathode but with a different velocity. These striations interfere and impede each other's progress as they move. The striations may be regular in time or the oscillations may be quite confused. Their frequencies range from 10^3 per second to 10^5 per second. The fluctuations in light intensity, at a point ranging from zero to the maximum value, are accompanied by oscillations in potential across the tube of some percent and synchronize with the fluctuations of light intensity where these are regular. It is Dieke's belief that a truly steady d.c. glow discharge is rare indeed. Where it occurs the Faraday dark space should sensibly be absent.

The oscillations are difficult to explain unless there is some cause for instability inherent in the glow discharge. They become a logical consequence of the situation once an overvolted or unstable cathode condition is assumed. In such discharges, as the initial glow discharge builds up on application of the potential, it begins as a Townsend discharge with a low secondary coefficient at the cathode. Once the cathode is cleaned up, the tube is overvolted and the autocatalytic breakdown begins. In this case, however, the long gaseous column yields the limiting resistor in the tube that prevents arc over. In fact, the tube as a whole has a positive resistance characteristic since energy derived from the gradient is required to maintain the long conducting luminous positive column. Electron attachment at these pressures usually does not throttle the discharge as in the more confined and less uniform gradients of the corona. In addition, a column of ionized gas has distinctly elastic and even resonant electrical properties and can thus be set into oscillation by electrical disturbances caused by instability. Plasma oscillations have long been recognized in ionized plasma. The ionic plasma oscillations have frequencies of the order of 10^5 cycles and up, depending on ion mass and density. Electronic plasma oscillations can occur at the lower pressures and these have frequencies in the microwave region.

One can picture the occurrences of the lower frequency oscillations observed by Dieke and Donahue as follows. As the cathode cleans up, the autocatalytic breakdown begins. There is a rapid overproduction of electrons in the negative glow. This builds up a steep gradient of potential relative to the positive column. It also holds back some of the positive charge in the Crookes dark space. The withholding of positive ions temporarily reduces the fall of potential in the cathode fall and slows the autocatalytic increase in positive ions and secondary electrons. Eventually the gradient between negative glow and positive column reaches such a value that a potential wave sweeps from this up the preionized positive column, ionizing as it goes. This is the negative striation of Dieke. Such potential waves have been produced in long tubes by Snoddy and Beams[11] with impulse potentials and are known in lightning discharge. Their velocity depends on the steepness of the potential gradient and on the density of ionization of the plasma. Once this wave of ionization has started towards the anode, the excess electron charge in the negative glow is reduced. The positive ions are released and the potential gradient at the cathode in the Crooke's dark space again begins to build up. When this is again at the value to overvolt the gap, the process repeats. The frequency of this oscillation will depend on pressure current density, overvolting, etc. When the negative voltage pulse from the cathode has reached the region of the anode fall, it produces a burst of ionization and a "reflected" wave of excess positive ionization, the positive striation of Dieke sweeps toward the cathode with, however, a different velocity. There are thus a succession of negative striations passing from negative glow to the anode, and of positive striations passing from anode towards the cathode, disappearing when they reach the negative glow. If these have the proper frequency and synchronize with instability pulsations in the Crookes dark space, then the regular oscillations observed by Dieke appear. If, however, they interfere destructively, the confused hash observed by Dieke results. There are a large number of modes of stable oscillations depending on the character of the discharge, the gases used, the pressure, length of tube, and current conditions. Under more special conditions the same cathode instabilities will call forth plasma oscillations at higher frequency. Emeleus and Armstrong[12] as well

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[10] G. H. Dieke and T. Donahue, Gaseous Discharge Conference, Brookaven, New York, Oct. 27–29, 1948; also ONR Report.

[11] Snoddy, Dieterich, and Beams, Phys. Rev. **50**, 469 (1936); **52**, 739 (1937); F. H. Mitchell and L. B. Snoddy, Phys. Rev. **72**, 1202 (1947).

[12] E. B. Armstrong and T. R. Niell, Nature **160**, 713 (1947); **163**, 59 (1949).

as Wehner,[13] by properly arranging the electrode disposition at very low pressures, were able by regenerative methods to produce electron plasma oscillations in the microwave region. On the basis of this picture, striations and the nature of and function of the Faraday dark space become clear. The Faraday dark space is connected with the cathode instability and represents the transient dark phase of the region between glow and column while the potential builds up. Since in other phases of oscillation it does not exist, the dark space is never completely dark. It is dark compared to the negative glow and positive column.

In the glow discharge it may be noted that the behavior of the discharge is determined largely by the electrically resonant properties of the tube, the function of the cathode instability being to furnish the driving force. That is, unless the cathode is in a state to furnish more complete breakdown by a chain reaction, the energy is not available for setting into motion the oscillations occurring. It is this important role of the cathode instability which has up to the present been lacking for an adequate explanation of these phenomena.

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[13] G. Wehner, submitted for publication Rev. Sci. Inst. (1949).

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Angular Distribution of Photo-Neutrons from Deuterium* †

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A study has been made, using 2.76 Mev Na^{24} gamma-rays, of the angular distribution of photo-neutrons from deuterium under approximately ideal conditions of low neutron scattering from the general surroundings into the detector. Results were obtained for two general methods of neutron detection, a BF_3 chamber and the Szilard-Chalmers reaction on $Ca(MnO_4)_2$. Assuming the neutron distribution to have, in the barycentric system, the form $I(\theta)=a+b\sin^2\theta$, the values of a/b obtained are 0.212 ± 0.008 for the first method and 0.203 ± 0.040 for the second, giving as a weighted average 0.211 ± 0.008. From this, the ratio of the photomagnetic cross section to the photoelectric cross section is calculated to be 0.317 ± 0.012.

I. INTRODUCTION

THE theory of photo-disintegration[1] of the deuteron predicts that for gamma-rays of energy appreciably smaller than about 50 Mev,[2] the distribution of photo-neutrons from deuterium should have, in the barycentric coordinate system, the angular distribution represented by $a+b\sin^2\theta$, θ being the angle between the direction of the photon incident on the deuteron and the direction of the neutron leaving the nucleus. This distribution is the combination of essentially two types of interactions, customarily referred to as the photoelectric effect, leading to the $\sin^2\theta$ term, and the photomagnetic effect, leading to a spherically symmetric distribution. Theory also predicts that for gamma-ray energies close to the threshold, which for deuterium is 2.237 Mev,[3] the photomagnetic effect predominates and thus the distribution should be isotropic. As the photon energy is increased, the photoelectric contribution becomes increasingly important and the distribution goes over into that represented by $b\sin^2\theta$.

Early research workers[4–6] showed quite readily that, for gamma-rays from ThC″ and radium, the distribution of photo-neutrons is anisotropic. However, due to either poor geometry, poor statistics, or both they were not able to show that the distribution found was actually a combination of a $\sin^2\theta$ part plus a spherically symmetric part. Myers and Van Atta,[7] using x-rays from a Van de Graaff electrostatic generator, which gave a continuous spectrum with a maximum energy of 2.43 Mev, first proved the existence of the photomagnetic component. They found the distribution was predominately isotropic as is to be expected for energies so near the threshold. Halban,[8] and Graham and Halban,[9] using the 2.62 Mev gamma-ray from RaTh, made a careful study of the relative intensities of photo-neutrons emitted in the 0°, 45°, and 90° directions with respect to the direction of the gamma-ray, obtaining the result: $a/b=0.26\pm0.08$. By means of a qualitative argument, based on the effect of neutron scattering within the heavy water sphere, an upper

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[1] See, for instance, H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8**, 124 (1936).

[2] M. E. Rose and G. Goertzel, Phys. Rev. **72**, 749 (1947).

[3] R. E. Bell and L. G. Elliott, Phys. Rev. **74**, 1552 (1948).

[4] J. Chadwick and M. Goldhaber, Proc. Roy. Soc. **A151**, 479 (1935).

[5] J. Chadwick, N. Feather, and E. Bretescher, Proc. Roy. Soc. **A163**, 366 (1937).

[6] J. R. Richardson and L. Emo, Phys. Rev. **53**, 234 (1938).

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[8] H. Halban, Nature **141**, 644 (1938).

[9] G. Graham and H. Halban, Rev. Mod. Phys. **17**, 297 (1945).