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# The Mechanism of the Negative Point Corona at Atmospheric Pressure in Relation to the First Townsend Coefficient

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On the basis of recent work by P. L. Morton and G. W. Johnson on ionization by electrons in divergent electrical fields, it is shown that at atmospheric pressure it is permissible to compute the ionization in electron avalanches by means of the Townsend expression $e^{\int \alpha dx}$ down to points of the order of $1\times 10^{-3}$ cm radius. The phenomena resembling a glow discharge, observed at atmospheric pressure with the negative points normally used, must be ascribed to ionization of the Morton type which can only be produced in the *positive space charge fields* built up at the point *later* in the course of pulse formation. The ionization at both positive and negative points must initially be of the Townsend type. This conclusion clarifies difficulties, and is consistent with the pulse build-up time of 0.4 microsecond just observed by W. N. English with a Synchroscope. An explanation is also given for the equality of starting potentials of pulses from positive and negative points in air, while in *pure* $N_2$ and $H_2$, the negative pulses start at much lower potentials.

THE work of Trichel,[1] Weissler,[2] and of Loeb, Kip, and Hudson[3] on the negative point corona in air and other gases at atmospheric pressure has established a close analog between its character and structure and that of the well-known glow discharge. This behavior, in contrast to the phenomena observed with a positive point corona under similar conditions, leads to inconsistencies in the earlier interpretations given.[1] The difficulty was introduced through the use of the function $e^{\int \alpha dx}$ in calculating electron multiplication in the divergent fields about gaps, with $\alpha$ representing Townsend's first coefficient for ionization by electron impact, and $x$, the distance traversed in the field. The function yields a maximum of ionization adjacent to the cathode surface.[1] On the publication of Morton's[4] important study concerning the ionization by electrons in highly divergent fields, the difficulty became more acute. Morton showed that the Townsend function could not be applied to fields whose divergence was such that the field changed by more than 2 percent over an electron free path. Not only did Morton show that the ionization in such cases could reach values of an order of magnitude more than given by $e^{\int \alpha dx}$, but he further showed that under these conditions the ionization *near* the negative point electrode was very small, becoming appreciable only at some distance from the point. Such a distribution of ionization is just the inverse of that given by $e^{\int \alpha dx}$. Thus the Morton process does not yield the conventional Townsend electron avalanches. Morton's findings are in excellent accord with the situation required to account for the observed mechanism near the cathode of a glow-like discharge. However, they introduce some difficulty when it is noted that the use of $e^{\int \alpha dx}$ nicely accounts for the streamer and other phenomena at a *positive* point of moderate diameter,[5] while the Morton conditions seem to apply to the *negative* corona from the same point, at fields of the same magnitude.

A comprehensive extension of Morton's initial studies over a pressure range from 0.01 mm to 760 mm pressure in pure $H_2$ and mercury free air has just been completed by G. W. Johnson[6] in the writer's laboratory, and will be published shortly. On the basis of the new data the writer was able to make some calculations which enable the difficulty properly to be clarified. It appears that at *atmospheric pressure* for all gases studied, the geometrical field conditions for concentric cylinders are such that the electrons remain *pretty well in equilibrium* in the electrical fields down to wire diameters of the order of $1\times 10^{-3}$

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[1] G. W. Trichel, Phys. Rev. **54**, 1078 (1938).
[2] G. L. Weissler, Phys. Rev. **63**, 96 (1943).
[3] L. B. Loeb, A. F. Kip and G. G. Hudson, Phys. Rev. **60**, 714 (1941).
[4] P. L. Morton, Phys. Rev. **70**, 358 (1946).
[5] K. E. Fitzsimmons, Phys. Rev. **61**, 175 (1942).
[6] G. W. Johnson, Phys. Rev. **71**, 278(A) (1947).

cm. With other geometrical configurations, such as hemispherical capped cylinders or confocal parabaloids,[7] the value of the critical point radius might be slightly larger, but not materially so. Thus, the use of $e^{\int \alpha dx}$ in calculation for most corona points commonly used at atmospheric pressure is justified, unless *space charge conditions* alter the fields materially.

This also justifies previous practice in computing the creation of the avalanche leading to streamer formation in *positive* point corona, which determines onset.[5] In such calculations, theory and experiment have always been in satisfactory agreement.[5, 6]

In the case of the *negative* corona the calculations for electron multiplication leading to evaluation of the onset threshold must extend beyond the first ionizing avalanches to which $e^{\int \alpha dx}$ can apply; for, unlike the streamer, or the burst pulse, the negative corona pulse builds up more gradually.* In this instance, at the threshold, the first electrons leaving the negative point region move outward into lower fields producing $e^{\int \alpha dx}$ electrons and positive ions as the static field requires. Photons produced by this avalanche, together with some positive ion impact on the negative point, then produce more avalanches, and a continuous or chain succession of such events builds up. During this period, however, the relatively slowly moving positive ions are approaching the point, building up a notable positive ion space charge at the point which is only partially neutralized by the rapidly moving secondary electrons and their progeny leaving the point. In consequence, there is built up a *very strong potential gradient at the cathode surface* which is *many times the geometrically fixed gradient starting the phenomenon.* There is nothing in the corona environment to prevent the development of cathode gradients from becoming quite comparable to those observed in glow discharges. When such gradients are achieved, in conformity with the Morton findings, the electrons then gain some twenty to a hundred electron volts of energy in ten to twenty electron free paths in the dark space. With ionization and excitation probabilities of the order of a few percent these electrons lose little energy. They thus do not ionize very much until they reach the weak field region beyond positive space charge. This mechanism yields the characteristic Crookes dark space and negative glow so often described.[1, 2, 3] Using $e^{\int \alpha dx}$, without the building up of a space charge and the Morton condition, as in the past, this observed condition was hard to understand.[1] Such a discharge will continue indefinitely with some fluctuations in magnitude until choked off by negative ion formation and space charge,[3] or until alteration of the cathode surface by positive ion bombardment reduces secondary emission below the operating threshold.[2] The mechanism indicated at once removes the conflict between the positive corona, operating with $e^{\int \alpha dx}$, and the negative corona operating as a glow discharge, in that, initially, $e^{\int \alpha dx}$ applies to both points but alters to Morton's condition as the discharge develops. The clarification, however, does more in that it makes possible an understanding of sputtering[2, 3] observed in negative coronas. With the positive space charge gradients the positive ions can strike the cathode with ten or more volts of energy instead of the estimated 1 volt following on the Townsend calculation.[3]

TABLE I. Data on the potential in volts for the beginning of bursts for positive and negative points ($Vg\pm$) and for the *onset* phenomena of Weissler ($V_{onset}\pm$).

| Gas | $Vg+$ | $Vg-$ | Self-sustaining corona $V_{onset}+$ | $V_{onset}-$ |
|---|---|---|---|---|
| $H_2$ | 3500 | 2800 | — | — |
| $N_2$ | 4800 | 3700 | — | — |
| Air (Weissler) | — | — | 5500 | 8000 |
| Air (English) | 5100±50 | 5000±50 | 5550±50 | 8000–10,000<br>Indefinite oscillographically, individual pulses still resolved |

It had been observed by Weissler that in *very pure* $H_2$ and $N_2$ the corona starting potentials were considerably lower for the negative than for the positive point. On the other hand, it has been generally asserted, without data being published, that the starting potentials for positive and negative points in air was about the same and higher than in pure $H_2$ and $N_2$. This is illustrated by the data of Table I. These data

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[7] L. H. Fisher and G. L. Weissler, Phys. Rev. 66, 102 (1944).

* Recent studies of the Trichel negative corona pulses in air by means of a Synchroscope with high sweep rate by W. N. English in this laboratory indicate that the unresolved pulses of Trichel do indeed build up gradually, rising to a peak and declining over a time interval of 0.4 microsecond, while streamers build up more rapidly.

represent the beginning of bursts for the positive points, $Vg+$, and Trichel pulses, $Vg-$, for the negative points as shown by oscillograph for air, together with the corresponding data for the *onset* phenomena observed by Weissler in $N_2$ and $H_2$. Weissler failed to specify his point diameter for the data given. He observed the onset visually and by current change for the *self-sustaining* coronas in $H_2$, $N_2$, and air. In this discussion the potentials for the *beginning* of pulses, $Vg$ only is of interest. W. N. English kindly has measured the potentials for room air by using a 0.5 mm point. This, it appears, was also the point that Weissler used. The values in volts are:

An explanation of this marked difference in behavior was indicated by Weissler,[2] but needs further clarification in the light of what has been stated above. There appear to be two factors present to effect such a change. First, in pure gases the secondary mechanisms responsible for onset of the *negative* corona are determined by secondary electron liberation by photoelectric effect from the cathode, by positive ion bombardment of the cathode, or by photoelectric ionization in the gas near the cathode. In the *positive* corona the fundamental secondary mechanism active is *only* photoelectric ionization in the gas leading to streamer, or burst pulse, production. Secondly, in air, electrons of low energy *do not remain free* but form negative ions of heat, of formation in the order of 0.2 volt.[8] In pure $H_2$ and $N_2$ electrons are free. Thus, from the viewpoint of initiating electrons, the pure gases merely require adequate fields to initiate secondary mechanisms near the point. The secondary liberation of electrons from a negative point in *pure gases* requires a relatively low field, since the photoelectric effect from the *cathode metal* is adequate in the relatively transparent gases to furnish such electrons at the start. With the discharge well developed, secondary electron liberation by positive ion impact on the cathode is also very effective. In the pure gases the photoelectric ionization *in the gas* is very meager, and it is not surprising to see that higher fields may be required for a discharge operating by this action only, in the case of the positive point in pure $H_2$ and $N_2$. In air, on the other hand, the heterogeneous character of the gas facilitates photoelectric ionization in the gas, so that the positive threshold could be lowered relative to that in pure $N_2$ and $H_2$, provided that Townsend's first coefficient is not materially altered by $O_2$. On the other hand this circumstance *lowers* the efficiency of photoelectric ionization *at the cathode* by gas absorption of the photons. It can also raise the work function of the cathode because of the action of oxygen on the surface. It is, however, hardly likely that at any time the *photoelectric action in the gas* can be the dominating element in negative point corona, though it, together with photoelectric action at the cathode, may help start the discharge in air. After space charges build up, positive ion bombardment doubtless predominates. Thus, in regard to secondary mechanism, the negative corona should usually have a lower threshold. However, neither of these discharges in air can start until the fields near the electrodes are sufficiently high so that a field strength to pressure ratio, $X/p$, exceeding 90, the value required to liberate electrons from the negative $O_2$ ions,[8] extends far enough out from the point to insure adequate electron ionization in the avalanches. This situation appears to be achieved in air at the starting potential for preonset streamers and burst pulses expected in positive corona.[5] Thus, it is this circumstance that probably fixes the value for the onset of *both* the *negative* and *positive* corona pulses at about the same potential, under conditions where, without this difficulty, the negative starting point could well be lower.

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[8] L. B. Loeb, Phys. Rev. **48**, 684 (1935). See also N. E. Bradbury and G. Bloch, Phys. Rev. **48**, 689 (1935).