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Pulses in Negative Point-to-Plane Corona

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The failure of W. H. Bennett working with very fine negative points and of G. G. Hudson working with larger carefully polished negative Pt points in clean dry dust-free air to observe the regular relaxation oscillator-like pulses reported by Trichel for negative points in room air led to a further study of the Trichel pulses. Certain results obtained by A. F. Kip in an earlier study of the Trichel pulses in room air have been added to the findings of Bennett and Hudson and are here reported. It was found by Kip and Bennett independently that the onset potentials and the current voltage characteristics of the corona showing Trichel pulses are independent of the metal and thus of the work function of the point. Bennett's studies indicate that the mechanism of the pulses depends entirely on the nature of the field about the point in air and that the pulses occur only in gases attaching electrons to form a space charge cloud of slowly moving negative ions whose time of movement across a critical region in the gap determines the frequency of the pulses. The absence of Trichel pulses in gases where electrons do not attach to form negative ions has independently been confirmed by G. L. Weissler in pure N_2, H_2 and A in studies to be published separately. It is further independently shown by Bennett and by Hudson that the regular Trichel pulses originating as they do in the gas require the presence of a source of triggering electrons. These can be furnished from fine points or by roughness on larger points through field emission, by very fine dust specks through the Paetow effect and probably by adequate photoelectric or thermionic emission from the point. Thus room air, yielding negative ions and providing ample numbers of fine dust specks for triggering, yields the regular Trichel pulses while clean, dry dust-free air, giving but rare dust specks, yields random bursts of pulses of irregular form. Observations of pre-onset phenomena by Kip and of the nature of the "active spots" and their action on the Pt point by Hudson are also reported. The theory of the phenomenon is reconsidered in the light of the findings and it is shown that the theory proposed by Trichel is applicable except as modified by the influence of the negative ion space charge and the necessity of triggering electrons. The appearance of what seems to be an incipient retrograde streamer process of the type pictured by Loeb and Meek in their study of long sparks is reported in the observations by Kip and Hudson of negative coronas from larger points well above onset.

Introduction

The initial study of negative point-to-plane corona by G. W. Trichel[1] revealed the presence of regular relaxation oscillator-like pulses in room air. These pulses appeared at or near corona onset with moderately small points at frequencies of a few thousand per second. They rapidly increased in frequency as the current increased with increasing potential and were distinguishable as separate pulses up to frequencies of a hundred thousand per second. The physical processes leading to the phenomena were explained in a tentative fashion by Trichel in his paper and appear in general to be substantiated. As will be seen below, the mechanism postulated, however, requires modification in some of its details. Trichel worked in room air with points of a limited range in size which were roughly polished.

At about the same time the above studies were being made, W. H. Bennett was independently making studies on extremely sharp points and extended them to include measurements in clean dust-free air. It was found that in these latter cases, the regular pulses did not occur at all times and this fact was communicated to Loeb early in 1940. Hudson working with larger points in dust-free air under Loeb's direction had also encountered this difficulty and was engaged in a study of the cause. Bennett suggested that the regular pulses probably required some kind of small surface imperfection on the duller points, and that the sharper points gave currents triggered by cold emission, a suggestion which proved fruitful as will be seen. Bennett's data on extremely sharp points follows.

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[1] G. W. Trichel, Phys. Rev. **54**, 1078 (1938).

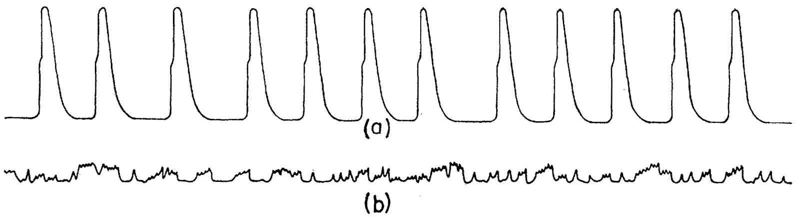

FIG. 1(a). Regular Trichel pulsations obtained with points having radius of curvature greater than about 0.002 centimeter. (The break shown in the steep wave front is probably instrumental in character. Pulses observed by Kip and by Hudson did not show this break, but were of the same form as photographed by Trichel, reference 1; (b) irregular forms of pulses obtained with points having radius of curvature of about 0.0004 centimeter. The jagged form is very similar to the irregularities in current obtained in cold emission from unconditioned points during "breakdown."

SHARP POINTS

Points were polished to form hyperboloids of revolution, and measured under a microscope. The radius of curvature R at the tip was used in calculating the field intensity, E_p, at the tip, in terms of the radius, the distance to the plane, x, and the potential between electrodes, V, by the same method used before in investigations of cold emission:[2]

$$E_p=\frac{2V}{R\log(4x/R)}.$$

Measurements were made with the point at various distances from the plane to test for consistency of data in order to insure that the support for the point was slim enough and that the disk used for the plane was large enough.

The regular forms of pulsation occurred at onset for all points with radii of curvature down to about 0.0025 cm, but a smaller and much more jagged form appeared for points with radii smaller than this. The pulsation forms are shown in Figs. 1(a) and 1(b).

The observed values of field intensity at the tip at onset are given in Tables I and II for various sharpnesses of point and various distances from point-to-plane. Tungsten and steel points were used. Table I is for point negative, and Table II is for point positive. Onset on positive could not be observed for points finer than $R=0.001$ cm because the current increased smoothly from less than 10^{-10} ampere, so the observations for the finer points on positive are for current equal to 10^{-8} ampere to correspond approximately to the average current at onset for the duller points. At distances of 0.1 cm, the finer points arced over without an onset, and were destroyed. Data on such points are missing. The finest points on positive could not be measured on negative because the shape of the tip changed too rapidly during the measurements.[3]

COLD EMISSION

These field intensities for the sharpest points are higher than those observed by Bennett for

TABLE I. *Negative onset field intensity in 10^5 volts per centimeter at tip of point for various plate distances x and radii R.*

x IN CM	R IN CM					
	0.00058	0.0012	0.0025	0.0050	0.0115	0.047
8	8.0	3.7	2.22	1.73	0.64	0.62
4	8.0	3.8	2.21	1.73	0.68	0.62
2	—	3.9	2.21	—	0.73	—
1	7.7	3.8	2.19	1.75	0.74	0.63
0.5	7.6	3.7	2.22	1.78	0.70	0.72
0.1	—	—	—	(1.86)	—	(0.79)
Av.	7.8	3.8	2.21	1.75	0.70	0.65

TABLE II. *Positive onset field intensity in 10^5 volts per centimeter at tip of point for plate distance x and radii R.*

x IN CM	R IN CM						
	0.00027	0.00058	0.0012	0.0025	0.005	0.0115	0.047
8	22.2	11.1	4.9	3.00	2.00	0.79	0.62
4	20.8	11.0	5.0	3.4	2.07	0.84	0.62
2	—	—	5.1	2.92	—	0.89	—
1	21.5	10.9	5.0	2.87	2.04	0.94	0.66
0.5	—	10.7	4.9	2.91	2.19	0.98	0.69
0.1	—	(10.6)	—	—	(2.18)	—	(0.89)
Av.	21.5	10.9	5.0	2.07	2.07	0.88	0.65

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[2] C. F. Eyring, S. S. Mackeown and R. A. Millikan, Phys. Rev. **31**, 900 (1928).

[3] W. H. Otto and W. H. Bennett, J. Chem. Phys. **8**, 899 (1940).

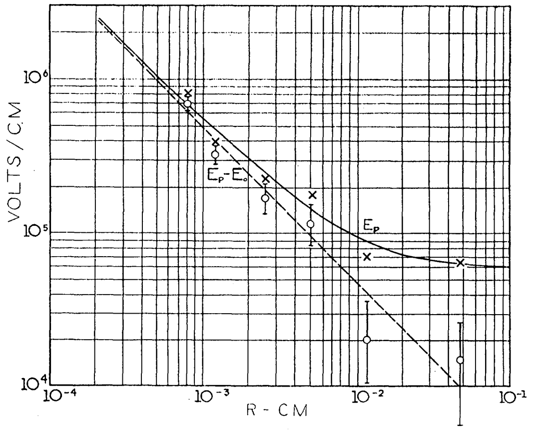

FIG. 2. Point negative, onset field intensity at tip of point. Full line with crosses represents the logarithm of onset field in volts per centimeter as a function of logarithm of radius of curvature of point at tip in centimeters. Dashed line with circles represents $\log(E_p-E_0)$ as function of $\log R$.

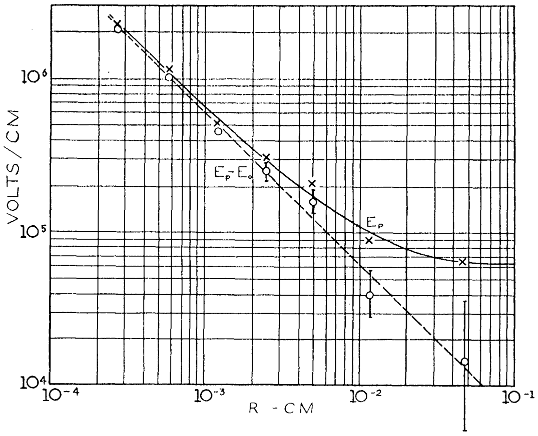

FIG. 3. Point positive, onset field intensity at tip of point. Full line with crosses represents the logarithm of onset field in volts per centimeter as a function of logarithm of radius of curvature of point at tip in centimeters. Dashed line with circles represents $\log(E_p-E_0)$ as a function of $\log R$.

equal currents in cold emission in vacuum from unconditioned copper spheres $\frac{3}{4}''$ in diameter,[4] and are about the same order as those published by Millikan and Lauritsen[5] for current-conditioned wires with more nearly the same radius. Mechanisms similar to those postulated by Bennett in his theory of magnetically self-focusing streams[6] probably occur to result in pitting a cathode point but not an anode point. The irregular pulse forms shown in Fig. 1(b) for the sharpest points on negative are thus seen to be due to the rapidly fluctuating cold emission currents during rapid successive breakdowns and fatigues amplified by ionization.

Since the onset field intensities are approximately constant for the duller points, but increase to a higher order of magnitude through the range to the sharpest points, it was supposed that the condition for onset on negative might be that the field must exceed some minimum field E_0 throughout an "ionization sheath" thickness x_0. If this be the case, then since the field near a hyperboloid of revolution of radius R varies with distance x according to

$$E=\frac{R}{R+x}E_p$$

the field will exceed E_0, throughout x_0, if

$$E_p-E_0=(x_0E_0/R).$$

The data were plotted in Figs. 2 and 3 by assuming a value of E_0 (50 kv/cm) which would give a negative slope of one to a plot of $\log(E_p-E_0)$ *versus* $\log R$. The data fit this assumption as closely as may be expected from the spread of the data.

This result, together with the observation that for the sharpest points on negative the pulse forms become those characteristic for cold emission, shows that Trichel pulses are caused by some mechanism in the air near the point rather than at the surface of the point, provided that sufficient trigger electrons are available. As discussed later, this mechanism is an electron attachment to form negative ions. The question of sufficiency of triggers is treated by Hudson's observations which follow.

THE ACTIVE SPOTS

The appearance of the regular Trichel pulses is found always to be associated with the concentration of the discharge at a single localized active spot which covers a small area as indicated by Trichel.[1] See Figs. 4(b) and 6(b). The size of such spots is never *more* than 0.2 mm in diameter. Larger areas of glow occur but are seen to be composed of multiple spots with the discharge

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[4] W. H. Bennett, Phys. Rev. **37**, 582 (1931).

[5] Millikan and Lauritsen, Proc. Nat. Acad. Sci. **13**, 45 (1928).

[6] W. H. Bennett, Phys. Rev. **45**, 890 (1934).

often jumping from one spot to the other. The oscillograph patterns in such cases indicate the presence of groups or bursts of pulses which are independent in phase and are often superposed. Smaller areas of 0.2 mm diameter or less are single active spots in room air. If the high field region of the tip is of 0.2 mm diameter or less, the production of *multiple* spots is hindered and in room air the appearance of single active spots is facilitated. Larger points give high field regions sufficiently extensive so that active spots can, but do not necessarily form at several points. If they do form, the discharge jumps from one spot to the next at low currents. With larger currents one or more spots may be active simultaneously on large electrodes. The currents for the same potential are, according to Kip, usually larger with regular Trichel pulses than when the discharge is interrupted as with multiple spots. Macroscopic sharp points, foreign material, finger prints, or moisture must be avoided. Kip found that points of brass, copper, aluminum, iron, and platinum all give Trichel pulses in room air, and Bennett found the same for tungsten, rhodium, and various alloys containing nickel, copper, zinc, tin and antimony. No *measurable differences in onset potential or current attributable to such differences in material were observed*, provided the points were properly "conditioned." The character of the "conditioning" process was never clearly understood but points run for some time in room air usually became "conditioned" unless subjected to the disturbing factors above mentioned.

THE EFFECT OF CLEAN DRY AIR AND THE ASSOCIATED PHENOMENA

When the studies were made in a clean container with carefully filtered air dried over liquid air or CO_2 snow, the regular Trichel pulses could not be obtained. Instead, at onset bursts of up to a dozen or more irregular pulses similar in shape to those recorded by Trichel were seen. Above onset the pulses were quite irregular in amplitude and frequency. The amplitude of these irregular pulses was greater than in the regular Trichel pulses and they were randomly spaced in time.

In the work of Hudson, unlike the earlier work of Trichel and Kip, the platinum point electrodes (of 0.5 mm diameter) were carefully polished at first with rouge, later with tin oxide. They were carefully inspected under 100-fold magnification and were found to show only a few very fine scratches.

Hudson found that by the time a smooth point had become "conditioned," it had also collected *several very small dust specks*. Accordingly a newly polished point was dusted with MgO powder whose particles were of the order of 0.01 mm in diameter, which was the size of the collected particles on a "conditioned" point. In room air this dusted point at once gave Trichel pulses that were constant in amplitude and frequency. As the discharge continued and the dust particles were broken up or thrown off, fluctuations appeared and irregularities were again observed. Observations were next repeated in air of varying humidity with smooth and rough points, both clean and dusted with MgO. In these tests the evacuated chamber was filled with different amounts of saturated water vapor from a side chamber containing distilled water. Dry air was then admitted from a high pressure cylinder. Values of 0, 45, and 100 percent relative humidity at about 22°C were used.

Dusted points always started by giving Trichel pulses but in dry air these rapidly gave way to the irregular type. In the presence of moisture the rough, dusted point continued to produce periodic pulses for 35 minutes or more, which was two or three times as long as with the smooth dusted point. When the irregularities began to appear it was found that the particles had largely been removed from the tip of the point. This observation, taken together with the fact that dusted points always started to give good pulses

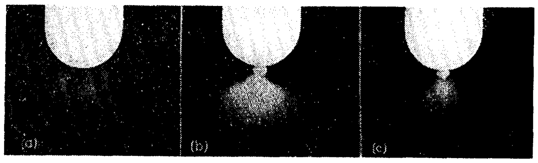

FIG. 4. Photographs of the negative point discharge. (a) A 6-min. exposure of the pre-onset glow at 4.07 kv. (b) Glow from main spot and also from a large dust speck near tip at 7.0 kv and 7 μa current. (The outline of the point was made by means of a mask over the print, the size and location of which were checked photographically.) (c) Appearance of active spot when regular pulses occur. With a shorter exposure than for (b) the dark space between the two parts of the glow can be seen.

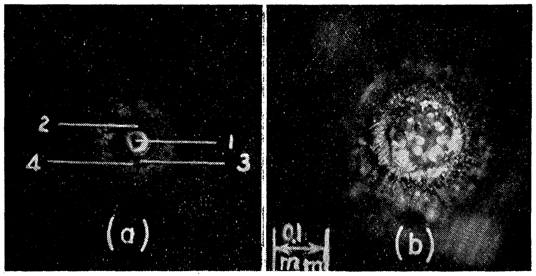

FIG. 5. (a) Photomicrograph of the tip of a 0.45 mm diameter Pt point after a 2¼-hr. negative run in partially saturated room air at 6.5 kv and 3 μa. A dark reflection is seen in the central smooth spot (1), which is surrounded by a heavy oxide ring (2). The narrow clear zone (3) and the thin outer dark ring (4) are also evident; (b) Negative point after a 3-hr. run in dry air at 10 kv and 17.8 μa. Several small, bright pits appear instead of a large bright spot as in (a).

in dry air, seems to indicate that the moisture in the air tends to hold the MgO specks on the point surface. It is interesting to note that the triggering dust specks usually occur at the side of the active spots. These enter as near as possible to the strong field region adjoining the spot. One can conclude that the presence of fine particles on the tip of the point is a necessary condition for the appearance of Trichel pulses. This explains why unconfined room air with plenty of fine dust and particles gave the pulses whereas in clean filtered air one had to wait a long time to capture such a speck. Larger dust particles such as lint, etc., as observed by Kip, of course spoiled the regularity by producing a fine point corona of its own. Kip with his telemicroscope of low resolving power did not observe the fine specks while Hudson using a hundredfold magnification found them. The function of the fine specks is obviously of the same sort as that observed by Paetow[7] in spark discharge. Here the specks of oxide became highly charged by ultraviolet light and by positive ions. These lead to bursts of electrons either produced by field emission, small sparks through the specks or by some short wave-length ionizing photon emission. These mechanisms obviously furnished the needed triggering electrons for the regular Trichel pulses. Why these electrons are needed and why the work function of the metal is of no influence will become clear in a discussion of the mechanism occurring. The effect of the triggering electrons is still further shown by the fact that when a clean point became "conditioned" by collecting dust the offset potential was lowered by as much as 10 percent.

PRE-ONSET PHENOMENA

Trichel[1] had observed that below a certain voltage pulses cease to be of constant frequency (the low limit was about 1000 per second) and became random, and spaced far apart in time (order of 1 second). This was confirmed by Kip. Kip used a preamplifier to look for evidence of small discharges before onset of the larger pulses. With a 0.318-cm diameter brass point and a gap of 4.2 cm in room air the following sequence was observed. At 11.7-kv current irregularities were first visible. There was, however, no detectable sudden onset at this voltage at which one could definitely say that irregularities appeared. It was later observed that this "pre-onset" current had associated with it a faint glow at a distance from the point as shown in Figs. 4(a) and 6(a). There was, however, no active spot next to the point surface. Increasing the potential to 13.89 kv increased the size of the oscillograph irregularities and increased the current from less than 10^{-9} amp. at 11.7 kv to 10^{-8} amp. at 13.89 kv. Above

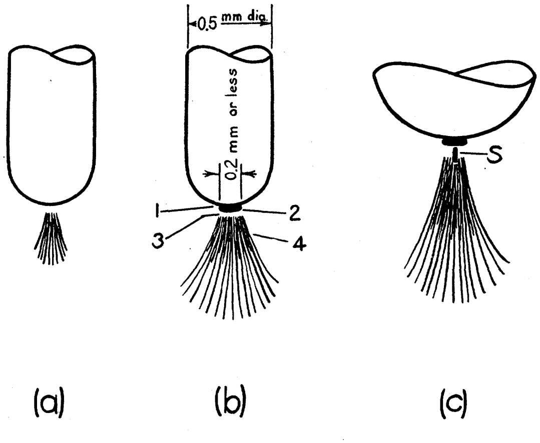

FIG. 6. Drawings of typical preonset and active spot negative corona phenomena. (a) Shows pre-onset glow also seen in Fig. 4(a), and after onset in Fig. 4(b), (b) shows the structure of the typical active spot accompanying Trichel pulses with Crookes dark space (1), negative glow (2), Faraday dark space (3) and positive column 4. (c) shows the incipient retrograde streamers with large points and high current densities.

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[7] H. Paetow, Zeits. f. Physik **111**, 770 (1939). See also L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley & Sons, New York, 1939), p. 498.

this the first single, random pulses began, and with a further increase in voltage the pulses became periodic as shown in Fig. 1(a) and the corona took the form of Figs. 4(c) and 6(b). The same weak glow discharge giving fluctuations that were not detectable without a preamplifier were observed by Hudson. Sometimes more than one such discharge would occur. With the microscope these discharges were clearly attributable to the presence of fairly large dust specks, Fig. 4(a).

EFFECT OF THE DISCHARGE ON THE POINT

After a short run with regular pulses the negative point begins to show the formation of a smooth bright spot where the glow is centered. This is surrounded by a dark ring. As the discharge continues in air the ring becomes thicker and wider. In dry air a run of about an hour produces another ring of larger diameter, brown or yellow in color and which may be separated from the heavier inner deposit by a narrow zone of clean platinum surface. Typical photomicrographs are shown in Fig. 5 and typical dimensions on a 0.45-mm diameter point are as follows: central bright spot 0.05-mm diameter; first dark brown or black ring 0.03 mm wide; clean zone less than 0.01 mm wide; outer dark ring 0.01 mm wide with outer diameter of 0.14 mm. The cathode glow diameter corresponds closely to the diameter of the central bright spot.

During one run of 4 hours in dry air with irregular bursts and a current of about 1.6×10^{-5} amp. a large amount of black material was formed on the tip in a spot 0.09 mm across. In this there were a dozen small pits each about 0.01 mm in diameter. This leads to an estimate of the removal of about 7×10^{14} atoms of metal for an equivalent charge transfer of 15×10^{17} electrons or ions.

The nature of these deposits was ascertained as follows. Heating the wire changed the color of parts of the deposit to black. Heating further to red heat caused the black material to disappear. Organic solvents did not affect the dark material, while chemical reactions of the deposit showed that it was not carbon or Pt black but apparently an *unstable* oxide of Pt. The formation of such oxides of Pt in an electrical discharge was reported by J. Piazza.[8] It is believed that the nitric oxides react with the Pt and that the molecules of oxide are blasted off the surface by the positive ions in the active spots. Where the discharge is irregular several active spots of limited size form and pitting results. The pitting may be about triggering points and may be caused by the mechanism of self-focusing beams.[6] When the regular pulses occur, aided by triggering electrons, the discharge spreads over a larger area and the localized pitting is not observed.

THE EFFECT OF ULTRAVIOLET LIGHT ON NEGATIVE POINT DISCHARGE

Ultraviolet light was obtained from a quartz Hg arc placed up to 6 inches distant from the discharge. The ultraviolet light appears to produce two effects working in opposite directions: It tends to increase the current at a given voltage by insuring a supply of triggering electrons at the point surface, and it tends to decrease the current by the production of low mobility ions in air. Either effect may predominate, depending on the size and surface conditions of the point, the maximum increase comes when the point is active at several spots. In this case the ultraviolet light tends to produce a single active spot working at a constant frequency, which in general increases the current apparently by furnishing the essential triggering electrons. More work is undoubtedly needed to clarify the question, but enough results were obtained to indicate some of the effects involved.

EFFECT OF HEATING THE POINT

The sharp bend in a V-shaped piece of wire heated electrically was used as a negative point. When cold it gave fairly good Trichel pulses but as it was warmed they became very irregular. When, however, the hot wire began to emit light visible in a darkened room the pulses again became regular. As the temperature became higher the frequency increased. This latter effect may be ascribed to decreased air density about the hot point; for, as Trichel showed, the frequency increases with decreasing gas pressure. On cooling the phenomena reversed in order

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[8] J. Piazza, Anal. Soc. Cient. Santa Fe **6**, 23 (1934).

except that the cold point no longer showed regular pulses as the point had been burned. This series of phenomena appears to confirm the conclusion that triggering electrons are needed for the appearance of Trichel pulses. Further work is needed on this question owing to the complicating effects of change in density which produced changes in the wave form of the pulses with fine points in some of Bennett's studies but not in the case of Hudson's studies.

THEORETICAL CONCLUSIONS

The mechanism postulated by Trichel[1, 9] for these pulses was as follows. When the field about the point becomes sufficiently great that the integral $\int_0^{x_0}\alpha dx$ has an appreciable value electron avalanches containing $\exp[\int_0^{x_0}\alpha dx]$ electrons and positive ions are formed by an initial electron moving out a distance x_0 from the point surface. The distance x_0 is such that beyond it with the diminishing field strength Townsend's first coefficient α for ionization by electron impact takes on negligible values (less than 1).[10] The mobile electrons formed continue to move outward beyond x_0, decreasing their drift velocity towards the anode as they recede. The relatively immobile positive ions (mobilities about 10^{-2} times those of the electrons) then remain behind as a space charge cloud moving slowly toward the point. The cloud has a density of ions depending on $\alpha\exp[\int_0^{x}\alpha dx]$ and therefore rises nearly exponentially at first to a maximum and then declines rapidly as α decreases and before x_0 is reached. If the density of the ionization in the avalanche reaches a sufficient magnitude two effects occur. The number of photons produced in the avalanche of electrons becomes large enough to produce effective photo-ionization in the surrounding gas. Simultaneously the density of the $\alpha\exp[\int_0^{x}\alpha dx]$ positive ions produced and left behind by the avalanche electrons increases and gives a strong space charge between the tip and the electron avalanche. This cloud of ions is being slowly (in comparison to electron velocities) drawn into the point where each ion has the probability γ of producing a secondary electron on impact with the point. This chance γ is none other than Townsend's coefficient for electron liberation by positive ion impact on the cathode. If the combination of the photoelectrically produced electrons in the gas and from the point together with the $\gamma\exp[\int_0^{x_0}\alpha dx]$ electrons furnished by ion impact exceeds unity then the discharge at the point could become self-sustaining, for these new electrons can themselves start avalanches which in their turn will furnish more positive ions. Under such conditions positive ions can proceed to accumulate in the gap and augment the positive space charge mentioned above. This charge *increases* the field close to the point, and increases α over very short distances next to the point. It reduces the field strength beyond the positive space charge, thus bringing x_0 closer to the point. The ionization beyond the space charge is thus reduced and ionizations by the electron avalanche are retarded. The photo-ionization effectively spreads the later avalanches laterally over the point surface by starting new avalanches at points about the initial avalanche.

This original picture of Trichel[1] is, however, not entirely satisfactory as the results here given show. First as pointed out by W. H. Bennett[11] the Trichel pulses require the presence of slow negative ions in order effectively to choke off the discharge. This is borne out by the fact that the pulses occur only in gases where electron attachment occurs. They are not observed in pure H_2 as reported by Bennett,[10] nor in H_2, N_2, or A as found by Weissler. Furthermore, the low frequency limit of the Trichel pulses is that to be expected from the time of movement of *negative* ions in the existing fields from point-to-plane. Such times have actually been measured for the transit of positive ions with a positive point-to-plane arrangement by Kip.[12]

In the second place if the triggering of the new discharge were caused primarily by the liberation of electrons by positive ion impact as postulated by Trichel, the Trichel pulses would depend very critically on the nature of the point surface and on γ. Doubtless this secondary emission does constitute *one* of the means of liberation. How-

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[9] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley & Sons, New York, 1939), p. 515 ff.

[10] L. B. Loeb and J. M. Meek, *Mechanism of the Electrical Spark* (Stanford Press, 1941), p. 127,

[11] W. H. Bennett, Phys. Rev. **58**, 992 (1940).

[12] A. F. Kip, Phys. Rev. **55**, 549 (1939).

ever, since the positive ions are largely drawn into the point before the negative ion cloud has time to become ineffective* the low value of γ and the resulting statistical fluctuations in secondary emission are such as to be inadequate regularly to set off the corona pulses. Thus the pulses observed will be irregularly spaced in time, and frequently interrupted. Set off by chance secondary electrons after intervals in which the negative charge has sufficiently dissipated, the resulting pulses will vary in amplitude, larger pulses coming from longer intervals of dissipation. Were adequate numbers of electrons always on hand, the amplitude and frequency of the pulses would only be determined by the minimum time of clearing for re-ignition, the pulses thus being small and close together as observed by Trichel on increasing the potential. An adequate supply of triggering electrons for the regular Trichel pulses must then be furnished by outside agencies such as field emission from small rough points, ultraviolet light of adequate strength or by the Paetow effect[7] produced by minute specks of oxide. This explains clearly the observations by Kip, Hudson, and Bennett showing independence of γ, the effects of dust, etc., and the short irregular bursts of pulses when clean dry air is used with smooth points. The currents obtained by the regular Trichel pulses which are of uniformly smaller amplitude are, however, larger than those with the larger irregular bursts of discharge as the latter are interrupted frequently as Kip observed.

Even in the case of extremely sharp points where cold emission provides far greater electron currents from the point than required for triggering, the principal effect is that the irregular form of the cold emission current produces a correspondingly irregular pulse form instead of the regular Trichel pulses. The negative ion space charge still acts to control the number of ionizations per initial electron: $N=\exp[\int_0^{x_0}\alpha dx]$ in the distance x_0. This distance x_0 is not decreased much by a large increase of the priming cold emission current, because the exponential form of the expression requires a small change in x_0 to compensate a large change in the initiating electron current to sustain any given *average* negative ion space charge density.

In other words, the very disruptive nature of cold emission during breakdown is ballasted by the strongly controlling effect of the negative ion space charge.

The lateral spread of the discharge out to 0.1 mm in the high field region near the triggering dust speck can be explained as due to photo-ionization in the gas and the concentration of the discharge in a layer close to the point by the nature of the field and space charges. Its size is determined by the rate of propagation of the photoelectric ionization laterally and the duration of the discharge before it is interrupted by negative ion space charge.

The purple glow occasionally observed outward of the larger points below onset with no active spot by Kip and by Hudson is now to be ascribed to specks of dust or fine points as shown by Hudson. These points emit a stream of electrons that become visible by cumulative ionization and space charge formation well out in the wider high field regions beyond the point. The glows occur at potentials sufficient to cause the fine points to become emitters before pulses can normally originate at the large point surface.

At larger points there are visible in the negative point corona before onset accompanying the Trichel pulses what appear to be active spots showing negative glow, Faraday dark space and positive column as observed by Trichel, with, however, a bright radial blue streak in the center starting from the edge of the column towards the point. The streak extends back toward the cathode into the Faraday dark space.† While it could be associated with the triggering dust speck in the Trichel discharge, the position of the speck at the side as well as the conditions of its occurrence indicate a more interesting explanation. It is illustrated in Fig. 6(c). It occurs well above onset with larger points having a larger high field region. It is thus to be ascribed to the

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* The negative space charge cloud need not cross to the plane to be ineffective. In fact Trichel found the frequency independent of gap length. The cloud must move sufficiently far away from the point in a weak field to exert no more influence on the positive ion cloud. This may be a matter of one or two mm with the points used here.

† It must be noted that visual and photographic observations record as superimposed many repetitions a *sequence* of events in a pulse cycle. Care must be used in interpreting such composite pictures as they record phenomena separated in time and space as if simultaneous.

attempts of the electron avalanches to initiate the retrograde streamers which are the forerunners of negative point breakdown with larger points.[13] They result from avalanches which would cause breakdown by positive streamers in a larger uniform gap. The streamers cannot advance all the way to the point cathode owing to the positive space charge which accumulates before the whole discharge is choked off. For still larger points the retrograde streamers reach the point and may cause breakdown.

The authors wish to express their appreciation to Makio Murayama, of the University of California Institute of Experimental Biology, for his valuable assistance in obtaining the photomicrographs.

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[13] L. B. Loeb and J. M. Meek, *Mechanism of the Electrical Spark* (Stanford Press, 1941), pp. 82, 87, 99, 170.

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Zeeman Effect Data and Preliminary Classification of the Spark Spectrum of Praseodymium—Pr II

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The Zeeman effect of praseodymium has been studied at fields up to 95,000 oersteds over the range 2400 to 7100A. g and J values have been determined for 74 Pr II levels from resolved Zeeman patterns of 141 lines. With these data, together with new wave-length data from the M.I.T.-W.P.A. Wavelength Project which have been applied to the spectroscopic interval sorter and interval recorder, a quadratic term array has been set up which accounts for 312 lines. This array is consistent with King's temperature classification of the lines and with all previous hyperfine structure observations. It is self-consistent in g values to an average deviation of 0.005 unit, and in wave numbers to an average deviation of 0.08 cm^{-1}. Previously published hyperfine structure measurements were found insufficiently precise to aid the classification, but were of value in its verification. The lowest term of Pr II is found to be $f^3({}^4I^\circ)\cdot s-{}^5I^\circ_4$. Most of the strong lines showing hyperfine structure arise from the f^3s configuration.

THE spectra of praseodymium have long defied classification, both because of the complexity of this rare-earth atom, and because many of its lines show hyperfine structure difficult to measure. White[1] has published extensive and valuable data on the hyperfine structure of Pr II, but these prove to be not quite precise enough to establish a classification.

The *M.I.T. Wavelength Tables*[2] list 2708 strong lines of praseodymium, and the unpublished W.P.A. card catalog at M.I.T. contains 3454 lines of all intensities assigned to the element. Actually the spectrum is so rich that the number of observable lines is limited only by the difficulty of distinguishing true lines from bands. The available description of the spectrum between 8000 and 2400A is fairly good, though limited in wave-length precision by the difficulties of measurement introduced by partially resolved hyperfine structure patterns (h.f.s.). Unless wave-length values accurate to ±0.003A can be obtained, it is impossible in so complex a spectrum to determine which is the correct quadratic array of the many obtained from the combination

TABLE I. *Fields for various spectrograms.*

SET NO.	FIELD	SET NO.	FIELD
Z 41 *H*	95,000 oersteds	*Z* 47	89,900 oersteds
Z 41 *L*	72,340	*Z* 48	87,400
Z 42	90,860	*Z* 63	89,290
Z 44	91,500	*Z* 73	87,540
Z 45	91,500	*Z* 75−*p*	85,510
Z 46	86,400	*Z* 75−*n*	87,970

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[1] H. E. White, Phys. Rev. **34**, 1397 (1929).

[2] (John Wiley and Sons, New York, 1939.)

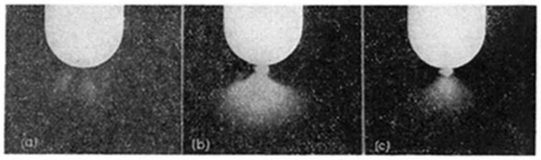

FIG. 4. Photographs of the negative point discharge. (a) A 6-min. exposure of the pre-onset glow at 4.07 kv. (b) Glow from main spot and also from a large dust speck near tip at 7.0 kv and 7 μa current. (The outline of the point was made by means of a mask over the print, the size and location of which were checked photographically.) (c) Appearance of active spot when regular pulses occur. With a shorter exposure than for (b) the dark space between the two parts of the glow can be seen.

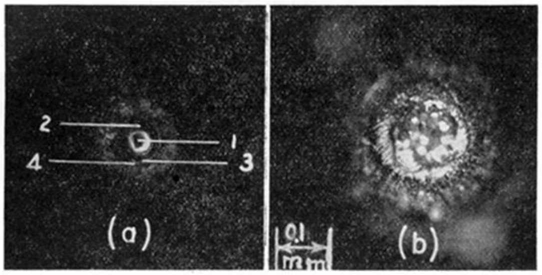

FIG. 5. (a) Photomicrograph of the tip of a 0.45 mm diameter Pt point after a $2\frac{1}{4}$-hr. negative run in partially saturated room air at 6.5 kv and 3 μa. A dark reflection is seen in the central smooth spot (1), which is surrounded by a heavy oxide ring (2). The narrow clear zone (3) and the thin outer dark ring (4) are also evident; (b) Negative point after a 3-hr. run in dry air at 10 kv and 17.8 μa. Several small, bright pits appear instead of a large bright spot as in (a).