Positive and Negative Point-to-Plane Corona in Pure and Impure Hydrogen, Nitrogen, and Argon

GERHARD L. WEISSLER
Department of Physics, University of California, Berkeley, California
(Received January 16, 1942)

To extend knowledge concerning the positive and negative point-to-plane corona, studies were made of the discharge in very pure H_2, N_2, and A. Neither pre-onset streamers nor burst pulses were observed in pure H_2 and N_2, in accordance with present theories of these effects. At high fields weak streamers developed which ultimately led to breakdown. Adding traces of O_2 to either H_2 or N_2 at once produced weak pre-onset streamers, and at higher concentrations produced burst pulses. Trichel pulses, which occur in properly triggered corona discharges in gases which form negative ions, are not observed in pure H_2 and N_2 but are immediately produced upon the addition of traces of O_2. For these gases the potentials for negative corona were observed to be lower than for the positive corona. In the case of argon, it was found that with positive point potential the first streamer formed was intense enough to cause spark breakdown, while with the point at a negative potential a heavy arc replaced the corona. Contamination of the argon with H_2 or N_2 introduced streamers for the positive corona which showed all the characteristics of those formed in air. This effect is attributed to the suppression of metastable atoms in the argon due to the presence of the impurity. For the negative corona small amounts of these gases (0.1 to 0.5 percent) prevented arcing and yielded a strong corona with glow discharge characteristics but no Trichel pulses. Addition of sufficient O_2 causes argon to act in all respects like air except that the onset potentials were much lower than in air. A clean-up of impurities in the negative corona in H_2 is shown to be due to formation and absorption of water vapor. The etching of negative points in the discharges in pure gases appears to be related to the sputtering process.

INTRODUCTION

THE application of newer techniques to the study of point-to-plane coronas in air has, as a result of recent studies,[1] revealed a series of mechanisms active in the individual cases of the discharge which depend on photo-ionization and space charge formation for their interpretation. In order to elucidate the mechanisms and to confirm the theories put forth, it seemed desirable to extend the studies to pure free electron gases of widely different photoelectric characteristics. This was especially important in view of the fact that one of the mechanisms, streamer formation, appears to be responsible for the sparking mechanism in uniform gaps above $pd=200$ (mm·cm) in air.

Investigations of the positive and negative point corona phenomena in the highly purified gases H_2, N_2, and A were undertaken. The results obtained indicated the value of studies with the admixture of certain impurities.

The results of W. H. Bennett[2] on the purification of H_2 by the negative corona and the attendant phenomenon of etching of points made it desirable to investigate these questions.

All measurements were made in Pyrex tubes, highly outgassed by being baked out, subjected to glow discharge in an induction furnace, and the pure gases then introduced into the tubes which were sealed off subsequent to filling. A cross-sectional diagram of a typical tube is shown in Fig. 1. Pt points, cylindrical in form with a hemispherical end carefully polished under the microscope with tin-oxide were used in the measurements. The platinum plates were 4 cm in diameter, with tungsten leads. The gap length ranged from 3.1 to 4.6 cm. The walls were shielded by evaporated thin gold films and all metal parts were heated to dull redness for approximately three hours with an induction furnace. Unless otherwise stated, all work was done at 760-mm Hg pressure and 22°C.

The tubes were filled with tank H_2, N_2, or A that had been passed over a conventional purifying train and liquid air, mercury being carefully excluded. In the case of N_2 a W filament in the sealed off tube was heated to incandescence for 20 hours to remove the last traces of O_2.

The d.c. high potential power supply was of the same type as the one employed by Sanders;[3]

[1] G. W. Trichel, Phys. Rev. **55**, 382 (1939); L. B. Loeb, and A. F. Kip, J. App. Phys. **10**, 3 (1939); L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley & Sons, New York, 1939), p. 520.
[2] W. H. Bennett, Phys. Rev. **58**, 992 (1940).
[3] F. H. Sanders, Phys. Rev. **41**, 667 (1939), Fig. 1.

it was stabilized by an electronic stabilizer of the saturable core reactor type to better than one percent above 5000 volts. The discharge was observed visually by a telemicroscope (70×), and the electrical pulses were recorded by an oscilloscope[4] which was connected across a resistor between the plate electrode and ground.

POSITIVE CORONA

In order to analyze the behavior of the discharges in pure free electron gases and in contaminated gases it is necessary to recall some of its salient features as found in air.

The streamer[5] which characterizes the positive corona in air depends on the first Townsend coefficient, the field strength, and mainly the efficiency of photo-ionization in the gas. The positive ion space charge left behind by a streamer tends to choke off further streamer formation and gives rise to the laterally spread burst pulse corona. The crucial phenomenon, photo-ionization in the gas, occurs most efficiently in mixed gases or in gases where metastable states are abundantly produced.

Experimental Results in H_2

In H_2 with a gap of 3.1-cm corona onset occurred at 3500 volts, showing a very feeble localized light spot of 0.005 cm in diameter on the point. In air under the same geometrical conditions one observes a corona glow spread uniformly over the tip of the point. In the potential region of corona onset, streamers were not observed, and the discharge seemed to be a succession of electron avalanches which formed in the relatively localized region of highest field strength at the tip of the point. Photo-ionization in the gas seemed inadequate to spread the glow over the whole tip of the point. At corona onset no pulses of definite character could be detected with the oscilloscope. With a 4-stage amplifier an uninterrupted succession of small irregular kicks was observed which may be attributed to the avalanches approaching the point.

At 9000 to 10,000 volts the fields were such that weak streamers could form which increased in length and intensity with increasing fields and at higher potentials led to a spark.[6]

The addition of varying amounts of O_2 (less than 0.1 percent to 1 percent) to the H_2 immediately resulted in the formation of pre-corona onset streamers. These increased gradually in strength and number on raising the potential such that they could be seen visually as what is later in Table I termed a "streamer-corona." On further raising the potential the streamers finally led to a spark. Increasing the percentage of impurity again gave pre-onset and onset streamers which had a higher intensity than those for lower concentrations of O_2 in H_2. At potentials above corona onset further streamer formation was not observed, and the discharge degenerated into a burst pulse corona as described by Trichel and Kip. At still higher potentials breakdown streamers occurred. The potential range between the appearance of the burst pulse corona and the

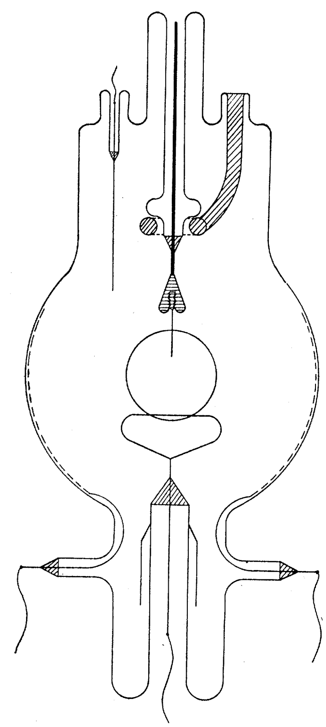

FIG. 1. Cross section of a typical discharge chamber, showing the point-to-plane gap which can be viewed through a plane window, the auxiliary W point in the upper left-hand corner, and the evaporated gold films which served shielding purposes.

[4] A. F. Kip, Phys. Rev. **55**, 549 (1939), Fig. 1B.
[5] A. F. Kip, Phys. Rev. **55**, 545 (1939).

[6] These streamers are later referred to as "breakdown streamers."

breakdown streamers is broadened with increasing amounts of O_2 impurities in H_2. Subsequent additions of O_2 led to an extension of the discharge area over the point. The currents in H_2 contaminated with O_2 were smaller than those in pure H_2 (Fig. 2).

For the interpretations of these results it seems profitable to recall that photo-ionization in the gas occurs most readily in mixed gases or in gases in which metastable states are abundantly produced. The intense photo-ionization in a mixed gas is due to the fact that one constituent has an ionization potential which is lower than the higher states of excitation of another constituent. In a pure gas such as H_2 one should expect very little photo-ionization. Since photo-ionization in the gas is the main mechanism to propagate a streamer from the high field region close to the point into the low field region several millimeters away it is not surprising to find that no streamers were observed at or before corona onset. The addition of 0.1 percent O_2 or more to H_2 realizes the state of a mixed gas, the efficiency of photo-ionization increases with increasing amounts of O_2, as is borne out by the fact that the intensity of streamers in successive mixtures also becomes greater. One percent O_2 in H_2 produced such intense streamers at corona onset that they were then able to leave a sufficiently large positive space charge behind such as to choke off further streamer formation by means of a considerable reduction in field intensity. The discharge then chose the way of least resistance and spread laterally over the point in the form of a burst pulse corona. To some extent this lateral extension of the glow is facilitated by the diffusion of negative ions which in turn produce triggering electrons for the formation of new avalanches the sum of which then constitutes a burst pulse.

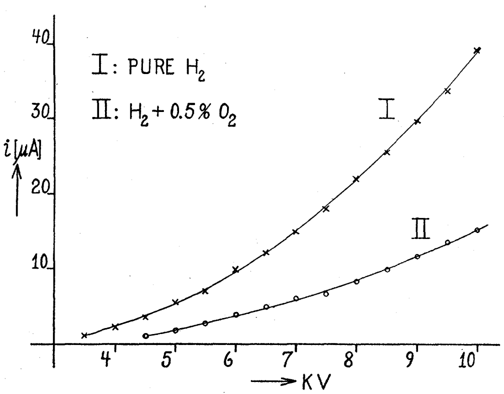

FIG. 2. Current-voltage characteristics for positive corona in pure and impure H_2, gap length 3.1 cm.

When the field is increased to the point where the positive ion space charge region is cleared in time to receive new initiating electrons from the burst pulse glow,[1] and it is increased such as to counterbalance the space charges, streamers will again appear. Under these conditions of higher fields the streamers will be sufficiently vigorous to cross the gap, form a cathode spot, and start an arc- or spark-breakdown.

It should be noted in Table I that the onset of an avalanche corona in pure H_2 occurs at 3500 volts, while the appearance of a streamer corona with 0.1 percent O_2 in H_2 requires 5000 volts. Subsequent additions of O_2 increased the efficiency of photo-ionization and therefore the ease of streamer and burst pulse formation, which lowered the threshold potential of corona onset.

The smaller currents in contaminated H_2 may be due to changes in Townsend coefficients and changes in ionic mobilities. A change in mobility would be more pronounced with O_2 in H_2 than in N_2 or A, owing to the great difference in ionic mobilities of O_2 and H_2. The ratio of mobilities in H_2 and O_2 is about five.

Experimental Results in N_2

In pure N_2 the conditions were not materially different from those in H_2: No pre-corona onset streamers were observed. Corona onset occurred at 4800 volts in form of a localized spot on the positive point. The oscillographic pattern was the same as in the case of H_2, namely, a sequence of irregular fluctuations of the electron avalanche type. Increasing the potential resulted in a brighter corona, which extended further toward the cathode in form of a continuous luminous channel, possibly due to the action of metastable atoms or active N_2. The potentials at which various phenomena appear is increased above those of H_2.

At 11,000 volts very faint streamers appeared, which give the well-known kicks in the oscilloscope superimposed upon the continuous corona ripple. In both N_2 and H_2 breakdown streamers could go across the gap at relatively low potentials without causing breakdown; but at

TABLE I. Essential data of the positive point-to-plane corona.

Gas	Pre-onset streamers	Corona Onset potential	Corona Visual character	Corona Burst pulses	Current‡ μA	Onset of breakdown streamers	Breakdown potential approx.
H_2 pure†	none	3500 v	localized*	none	4	10,000 v	18,000 v
H_2+0.1% O_2	yes	5000 v	intermittent streamer-corona	none	—	8,000 v	—
H_2+0.5% O_2	yes	4500 v	streamer-corona	none	3	9,000 v	—
H_2+1% O_2	yes	4000 v	uniform**	small	3	15,000 v	18,000 v
N_2 pure†	none	4800 v	localized	none	1	11,000 v	20,000 v
N_2+0.2% O_2	incipient streamers	4500 v	streamer-corona	none	1	9,300 v	—
N_2+1% O_2	incipient streamers	4800 v	localized, for higher v uniform glow	yes	1	12,500 v	20,000 v
Room-air†	yes	5500 v	uniform	yes	—	15,000 v	—
A pure††	none	none	none	none	—	—	3,500 v
A+0.1% H_2	yes	3300 v	localized	none	0.5	—	—
A+0.5% H_2	yes	3500 v	localized	small	0.5	—	—
A+1% H_2	yes	3450 v	localized	small	0.5	—	—
A+0.3% N_2	none	none	none	none	—	3,500 v	3,500 v
A+0.5% N_2	yes	3600 v	streamer-corona	small	—	4,600 v	4,600 v
A+1% N_2	incipient streamers	3500 v	localized	small	0.5	6,500 v	6,500 v
A+0.1% O_2	yes	3800 v	streamer-corona	none	—	4,100 v	4,100 v
A+0.4% O_2	yes	4500 v	streamer corona	small	0.6	—	7,000 v
A+1% O_2	yes	4000 v	uniform	small	0.6	—	15,000 v

* Localized glow, due to electron avalanches approaching the point in the highest field region.
** Uniform glow, caused by the burst-pulse corona.
† Gap length 3.1 cm.
†† Gap length 4.6 cm.
‡ Current at a potential which is about 20 percent above the corona onset potential.

higher potentials the number of streamers increased considerably until in N_2 at 20,000 volts they became strong enough to initiate spark breakdown.

The effect of O_2 impurities in N_2 (less than 0.1 percent up to 1.5 percent) was studied. The sequence of streamer and burst pulse phenomena closely duplicated those in H_2. The visible corona also changed from a localized glow in pure N_2 to a uniformly spread glow with increased amounts of O_2. The magnitude of currents did not change materially by addition of O_2 to N_2.

Although metastable states and activated forms of atoms exist, their abundance seems to be too small to increase the probability of photoionization with respect to that of H_2 to any appreciable extent, since no streamers were formed in the region of corona onset. The first Townsend coefficient takes on appreciable values in N_2 at distinctly higher values of the field strength as compared to H_2, which accounts for the differences in starting potentials. The complete absence of pulse formation in the pre-onset and onset region of both pure H_2 and N_2 means that no Geiger counter regime exists in those gases and confirms the conclusion that Geiger counter action is determined by space charge action.[7]

Experimental Results in A

In argon a spark crossed a gap of 4.6 cm at approximately 3500 volts. Neither pulses of any kind nor visible corona occurred. Since both H_2 and N_2 are known to quench the metastable states of argon by collisions of the second kind, varying amounts of these two gases were tried in argon. When 0.3 percent N_2 was admitted, a very few strong streamers occurred at 3500 volts followed by a spark at the same potential. An increase of N_2 to 0.5 percent gave streamers in the corona onset region which disappeared above 4100 volts and a localized corona with occasional burst pulses was observed. A spark, preceded by a few strong breakdown streamers, broke down the gap of 4600 volts. Increasing the percentage of N_2 in argon to values above 0.5 shifted the breakdown potentials to higher values. Argon

[7] C. G. Montgomery, and D. D. Montgomery, J. Frank. Inst. **231**, 447 (1941).

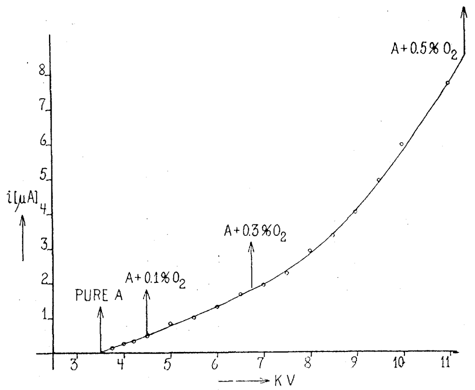

FIG. 3. Current-voltage characteristics for positive corona in pure and impure argon. The arrows indicate the upper limit of the current-voltage curve and the sparking threshold for a specific mixture of O_2 in A.

contaminated with H_2 showed essentially the same sequence of phenomena.

The addition of O_2 to argon again resulted in the formation of pre-corona onset and onset streamers without causing breakdown, while larger amounts of O_2 shifted the breakdown to higher potentials. The only difference was that above onset streamers still existed in the presence of a burst pulse corona (Fig. 3).

The current-voltage characteristics did not change materially for different amounts of N_2 or H_2 added to argon and were of the same type as those shown in Fig. 3 for O_2 in argon.

In argon the large production of metastable atoms distinctly enhances photoelectric ionization in the gas. In addition the first Townsend coefficient reaches effective values at very low values of the field strength, because electron impacts are highly elastic. For these reasons the first streamer was strong enough to cause a spark. The quenching of metastable states by H_2 and N_2 means a reduction of the efficiency of photo-ionization; as a consequence we were able to observe streamers which were stronger than commonly observed though not strong enough to cause an immediate breakdown. This is further supported by the fact that larger amounts of impurities destroy more of the metastable states, thus inhibiting formation of breakdown streamers at lower potentials and shifting breakdown to successively higher potentials.

Apparently the destructive effect of O_2 on metastable states is so great that streamers are so weakened at low potentials that they do not succeed in choking themselves off. With higher O_2 concentrations streamers were observed together with a burst pulse corona at higher potentials which indicates some choking of the streamers due to increased space charge formation. The presence of negative ions produced by O_2 appears to help spread the glow over the tip of the point at higher fields as distinguished from the case of H_2 and N_2 in argon.

Low Pressure Phenomena in H_2, N_2, and A

These gases were also studied at pressures of 300 and 100 mm Hg. The sequence of phenomena was the same as that at atmospheric pressure except that corresponding onset potentials were lowered as the pressure was lowered and that the visual appearance of the corona tended to become more diffuse (Fig. 8).

It is interesting to note that despite the greater diffusion at lower pressures, streamers can still form and propagate. This differs from streamer formation in sparking in a plane parallel gap in air[8] and must be ascribed to the high fields around the point which makes streamer formation still possible when it cannot take place in a plane parallel gap. The current-voltage characteristics were such that the slope of the curves increased with decreasing pressure due to the higher mobilities at lower pressures (Fig. 4) as observed by J. Zeleny[9] in gases of less purity.

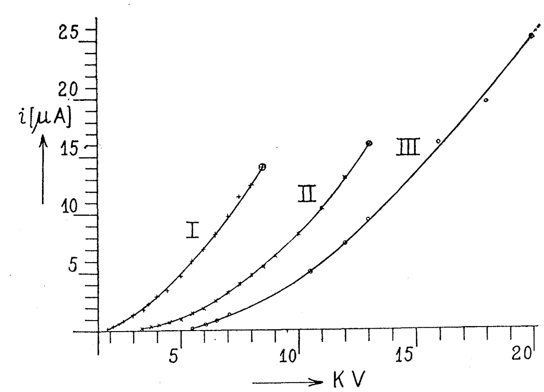

FIG. 4. Current-voltage characteristics for positive corona in pure N_2 at 3 pressures. I: $p=100$ mm Hg, II: $p=300$ mm Hg, III: $p=760$ mm Hg. The end points of curves *I* and *II* indicate spark breakdown, curve *III* ends at approximately 23 kv with a spark gap length 4 cm.

[8] L. B. Loeb, *Mechanism of the Electric Spark* (Stanford University Press, 1941).

[9] J. Zeleny, Phys. Rev. **25**, 304 (1907); J. Zeleny, J. Frank. Inst. **232**, 23 (1941).

NEGATIVE CORONA

The intermittent relaxation oscillator-like character of the negative corona has been ascribed to the formation of negative ion space charges[10] due to electron attachment to O_2 molecules.[11] In the very complex sequence of ionization phenomena in the concentrated field region owing to the differences in mobilities of positive and negative ions the negative ion space charge cloud acts to choke off the discharge until it is dissipated several millimeters into the gap. Thus we should expect to find the regular Trichel pulses appearing in all gases forming negative ions, the pulses becoming regular if the necessary triggering electrons[12] can be provided, either by field emission from rough points, fine dust specks,[13] thermionic emission, or photoelectrons. In the absence of electron attachment we should not expect to observe discharges interrupted by space charges since the high electron mobilities would preclude the formation of negative space charges.

For the same conditions as for the positive point the following experimental results were obtained.

Experimental Results in H_2

In pure H_2 negative corona onset occurred at 2600 volts, which is notably lower than the onset for the positive corona. The discharge began as a continuous discharge with no Trichel pulses or other discontinuities and appeared to be spread at onset uniformly over the tip of the point. This form of discharge was exceedingly unstable and sooner or later contracted to a concentrated point discharge in the region of highest field strength. The change was accompanied by a change in current by a factor of 10^3, it occurred more rapidly at lower pressures and more rapidly if the potential was raised slightly above the onset value. At 2800 volts the discharge appeared in the concentrated form within a few seconds, showing no indications of the Trichel mechanism and had all the characteristics of a glow discharge with Crookes' and Faraday's dark spaces, negative glow, and positive column. The onset of this discharge only is registered in Table II. At lower pressures or higher potentials the Crookes' dark space became distinctly visible. In the region from onset of the high current corona to breakdown two interesting facts were observed:

1. The concentrated discharge above onset tended to move continually over the surface of the point.
2. The form of the corona changed frequently and unsystematically from the concentrated glow to one which was uniformly spread over the tip of the point *without* change in current.

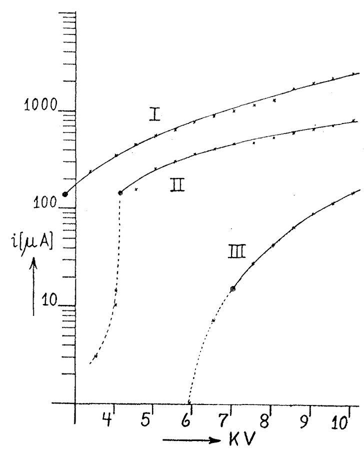

FIG. 5. Current-voltage characteristics for negative corona in pure and impure H_2. I: pure H_2, III: H_2+0.7 percent O_2, II: after clean-up run on auxiliary W electrode as discussed in the paragraph on clean-up corona. Lower end of the fully drawn curves marks onset of steady corona, dotted lines mark intermittent corona. Gap length 3.1 cm.

While the localized glow if it was not changing positions did not reveal any pulses, the uniform glow at the higher currents showed a succession of irregular inductive pulses of no definite character in the oscilloscope. On microscopic examination of a point run on a negative corona in form of a uniform glow with high currents, it was found that the whole tip over which the glow was visible was pitted with innumerable holes.

The introduction of the smallest amounts of O_2 immediately produced Trichel pulses, the onset of corona was 4200 volts, the currents were lowered to approximately one-half of their value in pure H_2 (Fig. 5). On increasing the amount of O_2 the onset of the steady corona was preceded by a region of interrupted Trichel pulses which

[10] G. W. Trichel, Phys. Rev. **54**, 1078 (1938).
[11] N. E. Bradbury, Phys. Rev. **44**, 883 (1933).
[12] L. B. Loeb, A. F. Kip, G. Hudson, and W. H. Bennett, Phys. Rev. **60**, 714 (1941).
[13] H. Paetow, Zeits. f. Physik **111**, 770 (1939).

TABLE II. Essential data on the negative point-to-plane corona.

Gas	Localized corona: Onset potential	Onset current μA	Visual character	Trichel pulses	Breakdown potential approx.	Peculiarities
H_2† pure	2800 v	140	unsteady glow*	none	—	alternation uniform+localized glow
H_2+0.1% O_2	4200 v	70	unsteady glow	yes	—	same as above
H_2+0.6% O_2	5800 v	2	unsteady glow	yes	—	same as above
N_2† pure	3700 v	90	steady glow**	none	14,000 v	
N_2+0.1% O_2	4300 v	50	steady glow	yes	—	
N_2+1% O_2	5500 v	0.1	intermittent***	yes	—	5,000 to 7,000 v intermittent corona
Room-air	8000 v	0.1	intermittent	yes	—	8,000 to 11,000 v intermittent corona
A†† pure	—	—	—	—	3,500 v	no corona
A+0.3% N_2	2500 v	200	steady glow	none	4,100 v	
A+1% N_2	3900 v	250	steady glow	none	—	
A+0.1% H_2	3200 v	400	unsteady glow	none	4,100 v	
A+1% H_2	3300 v	300	unsteady glow	none	—	
A+0.1% O_2	3000 v	1	steady glow	yes	—	
A+0.4% O_2	3000 v	0.1	intermittent	yes	24,000 v	3,000 to 6,000 v intermittent corona
A+1% O_2	3300 v	0.1	steady glow	yes	—	

* See experimental data in H_2.
** See experimental data in N_2.
*** Due to lack of triggering electrons.
† Gap length 3.1 cm.
†† Gap length 4.6 cm.

began at 5800 volts for 0.6 percent O_2 and was caused by a lack of triggering electrons.[12] The steady corona began at 7500 volts. With increasing potential the frequency of the Trichel pulses at onset increased. Larger amounts of O_2 required higher breakdown potentials and caused lower currents.

The difference in onset potentials for the positive and negative corona in pure H_2 is very distinct from those in air. In air the efficiency of photo-ionization is such that the discharge mechanism operates through electrons generated in the gas by photo-ionization in preference to the liberation of electrons from the cathode by positive ion bombardment. Since photo-ionization also determines streamer formation from positive points, we can explain the nearly identical onset potentials for both positive and negative corona in air by the fact that one mechanism is dominating in both cases. In the case of pure H_2 with inefficient photo-ionization in the gas the mechanism for maintaining the discharge from the positive point is different from that maintaining the negative corona as will be discussed more in detail in the paragraph on Positive and Negative Currents. Consequently the onset potentials for both signs of corona differ considerably.

Because negative ions are not formed in pure H_2 no Trichel pulses were observed.

The two above-mentioned facts on the behavior of the high current corona between onset and breakdown can be explained in the following way: In the event of insufficient photo-ionization secondary electron liberation would occur from the negative point by positive ion bombardment. The work function of the point and its conditioning would greatly influence electron emission, and the discharge would be sensitive to such alterations. Extreme variations of work function from 6 volt to 4 volt have been observed[14] between O_2-coated Pt surfaces and H_2-coated Pt surfaces. The continuous bombardment of Pt by positive ions effectively alters the work function even in a given gas. This instability of the surface would explain the movements of the concentrated discharge over the surface, and, together with the microscopically observed pitting, it is suggested that the discharge form of a uniform glow with high currents is caused by the action of one or more simultaneous localized spots, constantly changing their positions on the tip where every change was accompanied by an inductive kick in the oscilloscope. These changes as judged from

[14] C. W. Oatley, Proc. Phys. Soc. **51**, 318 (1939).

the approximate frequency of the pulses occurred so rapidly, of the order of several thousand for the time of persistence of vision, that the observations gave the illusion of a uniform glow. The validity of this viewpoint also seemed to be indicated by the fact that the current did not change during those transitions, being much too high for a Trichel mechanism, and that the uniform glow faintly showed a cathode glow, Faraday dark space, and positive column which extended laterally over the whole tip.

The interpretation of the very first mentioned transition of a low current uniform glow to the concentrated discharge with increased current, which was a continuous phenomenon, must lie in the conditioning of some spot in the high field region by positive ion bombardment leading to the formation of an adequate cathode spot.

Experimental Results in N_2

The sequence of phenomena in pure N_2 is essentially the same as in pure H_2. The onset potential of the localized corona was 3700 volts, which is higher than in H_2 but still lower than the onset of the positive corona in N_2. A schedule of the potentials at which various phenomena occur is given in Table II. As in H_2 the discharge began as a uniform glow at 3600 volts (not mentioned in Table II), it contracted in time visibly to the concentrated discharge with resultant increase in current by a factor of 10^3. The gradual transition of the discharge could be observed visually and the current increase accompanying this visual change noted. The localized corona differed from the case of H_2 only in remaining steadily at one position instead of moving over the surface.

The effects of small amounts of O_2 ranging from 0.1 percent to 1.5 percent introduced into pure N_2 were also studied. The smallest percentage of O_2 resulted immediately in Trichel pulses. Their choking action caused the currents to drop to approximately one-half of the magnitude in the pure gas (Fig. 6). The behavior in general was similar to that in H_2.

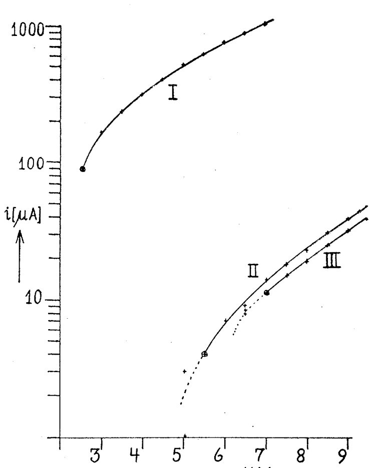

FIG. 6. Current voltage characteristics for negative corona in pure and impure N_2. I: pure N_2, II: N_2+0.8 percent O_2, III: after clean-up run, refers to the paragraph on clean-up corona. Gap length 3.1 cm.

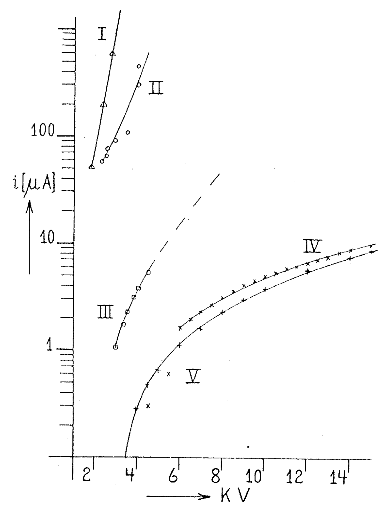

FIG. 7. Current-voltage characteristics for negative corona in pure and impure A. I: pure A, II: A+ <0.1 percent O_2, III: A+0.1 percent O_2, IV: A+0.5 percent O_2, V: A+1.5 percent O_2. The low potential end of the curves marks the "offset" potential of the steady discharge. Gap length 4.6 cm.

It is obvious that in the conditioning of the point surface there must be two mechanisms that work: One occurs in both H_2 and N_2 and appears to be a conditioning of the rested[15] point by positive ion bombardment giving increased electron emission. The other appears in H_2 only and results in a de-activation of the point by strong H_2-ion bombardment.

The lower onset in H_2 as compared to N_2 is to be expected from the difference in value of the first Townsend coefficient in the two gases.

[15] The initial uniform glow which transformed to the concentrated high current form did not appear on a surface after a discharge had been freshly interrupted. It apparently took a rest period of a few seconds to reform the gaseous film causing the uniform glow at low currents.

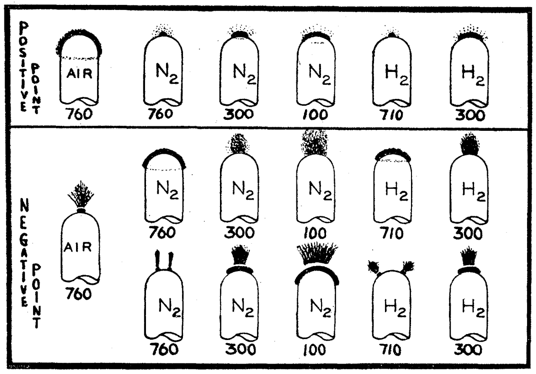

FIG. 8. Visual forms of corona discharges under indicated conditions in the onset region. Pressures in mm Hg. The forms in the second row show the uniformly spread discharge at low currents which contracts sooner or later to the concentrated forms of discharge with high currents which can be seen in the last row.

Experimental Results in A

For the same reasons as were mentioned in the discussions of the positive corona in argon we found that no matter whether the gap distance was 3.1 or 4.6 cm an arc discharge set in at approximately 3500 volts. It was continuous across the gap and no current fluctuations or pulses were observed. The current was of the order of magnitude of 10^3 microamperes. Once the arc had kindled, it persisted even with decreased potentials to a definite "offset" potential. The current voltage characteristics from onset to offset are shown in Fig. 7. Increasing the gap length had the effect of prolonging the time necessary for the arc to build up. This lag was of the order of seconds for a 3.1-cm gap and tens of seconds for a 4.6-cm gap. It must be pointed out that these results can only be achieved in argon of the highest purity as shown by the effects produced by traces of added gases.

The addition of 0.3 percent of N_2 to argon did not result in an arc immediately, but corona onset occurred at 2500 volts: Once started it continued to operate on reducing the potential to an offset at 1300 volts. On increasing the potential a few hundred volts above onset, a continuous transition to an arc was observed. Admitting larger quantities of N_2 merely shifted the arcing potential to higher values above corona onset. This may be ascribed to the quenching action of the metastable states by N_2.

Essentially the same succession of phenomena occurred on addition of H_2 to argon. There is one notable difference with this mixture which is the erratic movement of the corona glow from one spot on the tip of the point to another in rapid succession. This can also be seen oscillographically in the production of irregular inductive pulses. These indicate brief interruptions of the current but are definitely not due to a Trichel mechanism, since the currents were orders of magnitude larger than those connected with Trichel pulses. This motion of the discharge is again characteristic of the Pt point in the presence of H_2 as already stated. It does not occur with N_2 in argon. Increasing the amount of impurity of either H_2 or N_2 in argon decreases the slope of the current-voltage characteristics.

Admission of varying small amounts of O_2 (less than 0.1 percent to 1 percent) immediately initiated regular Trichel pulses, and the breakdown was at once raised to 10,000 volts, or more if the O_2-content exceeded 0.3 percent. Adding 1 percent of O_2 altered the appearance of the corona at onset, apparently through the nearly complete destruction of metastable states. In place of the regular Trichel pulses found with small amounts of O_2 present, due to the triggering electrons from the few metastables still existing, the larger amounts of O_2 caused the fluctuating corona observed by Hudson[12] on smoothly polished points to appear, when no triggering electrons from metastables were present. The currents in argon in the presence of O_2 were reduced below those in the presence of H_2 or N_2 in argon by a factor of approximately 10^{-3} as a result of the action of the negative space charges inhibiting the free flow of electrons and ions (Fig. 7).

As already mentioned above, in gases with efficient photo-ionization we find the same onset potentials for both signs of corona, because in both cases we find that electron generation in the gas is the primary mechanism for the maintenance of the discharge. Pure argon confirms this even stronger than air with its spark breakdown without preceding corona for the positive point at 3500 volts and its arc breakdown also without preceding corona for the negative point at 3500 volts.

The phenomenon of an offset markedly lower than the onset potential is characteristic of all negative corona phenomena. In H_2, N_2, and air the difference in potentials amounts to a few hundred volts for a 3-cm gap, while in argon it extends over a range of more than a thousand volts, probably due to the action of metastable states.

Low Pressure Phenomena for Pure H_2, N_2, and A

In the case of the negative corona a decrease in pressure resulted in the same sequence of phenomena as at atmospheric pressure. The corresponding potentials were decreased, as was to be expected, and the visual form was spread out (Fig. 8), emphasizing its glow discharge-like characteristics. The current-voltage curves again showed a steeper slope[9] for lower pressures due to increased mobilities (Fig. 9).

POSITIVE AND NEGATIVE CORONA CURRENTS

In pure gases transparent to photons it will in general be expected that near onset the negative corona currents would be several orders of magnitude greater than the positive corona currents for the reason that with a negative point the high field is concentrated about the cathode. Hence the necessary secondary ionization due to any one of three agencies, photo-ionization in the gas, photoelectric effect at the cathode, secondary electron emission by positive ion bombardment, is active in a high field region and ion multiplication is effectively ensured. In the case of the positive point the main source of electrons available for maintaining the discharge is the photoelectric effect at the distant plate. The low fields at the plate yield practically no electrons by positive ion bombardment and photoelectric emission from the plate is small. Hence, in the case of the positive point in H_2 or N_2, both of which fulfill the condition of being transparent to photons, secondary electron emission is small, and the observed currents at onset are small. For the negative point in H_2 and N_2 the positive ions are accelerated in the high field region toward the point without interruption by negative space charges and hit the point surface with energies 10 to 100 times higher than the energies with which they would strike the negative plate during a positive point corona; therefore, it is assumed that the second Townsend coefficient takes on relatively large values, thus yielding high currents (Figs. 4 and 9, also shown by current values in Tables I and II).

CLEAN-UP CORONA

Clean-up effects on H_2 contaminated with O_2 had been noted earlier. Bennett[2] ascribed them to the formation of an oxide of tungsten. The points used in our work were chiefly Pt but for test purposes an auxiliary W point was mounted in the chamber.

1. In the point-to-plane gap used in these measurements the point was of cylindrical shape with a hemispherical cap 0.05 cm in diameter, while in Bennett's work points of much smaller radius of curvature were employed, which naturally could not be shaped as accurately as the larger points.

2. The auxiliary W point was used so that the carefully shaped Pt point was not changed in form by the cleansing discharge, a procedure which was omitted by Bennett. Only under such carefully controlled condition can the observed current-voltage characteristic be completely ascribed to a change in the gas composition. For it follows both theoretically and from Bennett's observations that the Trichel mechanism which was used to detect electron attaching impurities

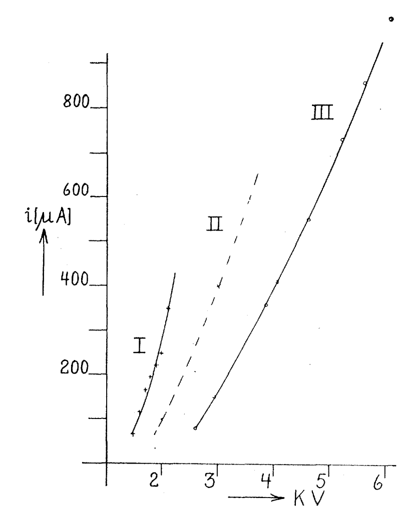

FIG. 9. Current-voltage characteristics for negative corona in pure N_2. The low potential end of the curves indicates "offset;" the high potential end does not indicate breakdown. Gap length 4 cm. I: $p=100$ mm Hg, II: $p=300$ mm Hg, III: $p=760$ mm Hg.

is not active on fine points. At the same time a severe etching of the fine points of Bennett was observed in the clean-up run. Thus it could not be determined whether the disappearance of the Trichel pulses was due to clean-up or to etching.

The procedure in this study was as follows: The chamber was carefully cleaned and filled with the pure gas, either N_2 or H_2. The phenomena occurring from corona-onset to spark breakdown were then observed in the main gap on the Pt point to serve as a check on previous results and as a control for purity. Then a small amount, around 0.4 percent, of O_2 was introduced into the chamber and the phenomena were recorded over the same potential interval as before. After this the clean-up discharge was run from the auxiliary W point for 8 to 12 hours at a high negative current. At the end of the run the condition of the gas was examined by a repetition of the test procedure with the clean Pt point.

Admitting traces of O_2 of less than 0.1 percent into pure H_2, one obtained in the test run the characteristic phenomena with positive and negative points detailed above. After the cleansing run with a W point no pre-onset streamers were observed for the positive corona and no Trichel pulses for the negative corona. Clean-up had obviously occurred and seemed to be complete.

If the impurities exceed 0.1 percent in H_2, the negative corona currents before clean-up fell to very low values due to Trichel pulse formation and the positive corona revealed streamers. Cleaning the gas with the discharge on the auxiliary W point restored in a large measure the purity of the gas; the currents, however, never reached the initial values in the pure gas, and incipient streamers were noted in the positive corona. It was clear that some clean-up had occurred, but with large amounts of O_2 it was never complete (Fig. 5). Use of a Pt point to produce the clean-up did not materially change the results of the clean-up compared with the W point, which seemed to indicate that the formation of tungsten oxide was not the primary mechanism for the clean-up action. This was substantiated by repeating experiments in N_2 which was contaminated by O_2. Under these conditions no clean-up was detected (Fig. 6). Therefore, clean-up in H_2 may be ascribed primarily to the formation of water. If the concentration of O_2 is low, the water formed by the discharge will be completely adsorbed by the baked-out and very hygroscopic walls of the Pyrex chamber. Above 0.1 percent of O_2 the amount of water vapor generated was too great to be completely adsorbed. Hence, one may ascribe the residual pulse formation to the remaining water vapor.

ETCHING OF THE POINT ELECTRODE

The occurrence of etching in pure nonreactive or inert gases about a negative point, as noted by Bennett, seemed peculiar owing to the high pressures used in these experiments and owing to the fact that Hudson[12] found pitting always associated with oxidation. While the phenomenon of sputtering occurs at the cathode of many discharge tubes, the sputtering becomes important only with higher cathode falls and low pressures. It is clearly a function of the energy of the incoming ions. In our experiments the positive ions strike the cathode with an energy not much in excess of one electron volt.

An attempt was made to correlate the degree of etching with some properties of the metals, and point electrodes of W, Pt, Cu, Al, and Pb were tested on the negative corona in gases H_2 and N_2 under standardized conditions (12-hour run, constant current of 1250 μa corresponding to a current density of about 1 amp./cm^2, gap length 3.1 cm). The points were carefully polished with tin-oxide and examined under the microscope. Etching occurred in all cases except Al and manifested itself in a symmetrical crater-like pit with a depression below the level of the point surface surrounded by a heaping up of metal at the sides. This heaping up may be due to the fact that a considerable fraction of the sputtered particles were reflected back and redeposited in the neighborhood of the region of impact owing to the high pressure of the gas molecules present. The amount of displaced material could be estimated roughly and appeared to be greater in N_2 than in H_2. No discoloration or other indications of chemical activity were observed. No simple correlation between any properties of the metals and the number of displaced atoms could be made. Etching in Al did not result in a crater-like pit, instead the whole surface of the tip of the point was roughened by a large number of fine holes which were caused by a discharge constantly changing its position of the point because of alterations of the oxide-coated surface film by the impact of positive ions.

The introduction of impurities made the investigations difficult because it immediately reduced the currents by a factor of more than one hundred, thus making the time of observation prohibitively long. There was no doubt, however, that etching also occurred in these cases.

While not many data as to the mechanism are at hand, the character of the process is sufficiently like the sputtering phenomenon in glow discharges to make one feel that one is here dealing with a type of sputtering occurring at relatively low positive ion energies, but in distinction to sputtering caused by positive ions of high energies in low pressure glow discharges, this sputtering occurs with low ion energies at high current densities.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to Professor Leonard B. Loeb, who suggested the problem, guided its progress, and helped in the interpretation of the observed data. The writer is also indebted to the Research Corporation of New York, under whose Research Fellowship Grant at the University of California the main part of this work has been completed.

PHYSICAL REVIEW VOLUME 63, NUMBERS 3 AND 4 FEBRUARY 1 AND 15, 1943

The Specific Primary Ionization of Cosmic Rays in Helium

WAYNE E. HAZEN
University of California, Berkeley, California
(Received November 17, 1942)

Values for the specific primary ionization of 46 cosmic rays in helium have been determined from cloud-chamber photographs. A magnetic field allowed separation into two groups: 21 electrons with energies near the energy for minimum ionization had a mean ionization of 7.33 ± 0.12 per cm, and 26 mesotrons with energies greater than the energy for minimum ionization had a mean ionization of 7.23 ± 0.12 per cm. The expected value for the latter figure, taking into account a logarithmic rise of ionization with energy, is 8.80 ions/cm. The experimental value for the minimum specific primary ionization in helium (corrected for the ionization in the vapor) is 6.5 ± 0.1 at N.T.P. Three protons were observed in the $H\rho$ range in which they can easily be identified; in this $H\rho$ range three particles constituted approximately one percent of the radiation.

THE primary ionization of electrons from radioactive sources has been determined by Williams and Terroux[1] in hydrogen and oxygen and by Skramstad and Loughridge[2] in nitrogen and neon. C. T. R. Wilson[3] counted the primary ions along the tracks of electrons with energies between ten and thirty kev. Theory predicts a logarithmic increase in ionization with energy when the kinetic energy is large compared to the rest energy. Kunze[4] failed to detect any rise in ionization in measurements on ten cosmic-ray particles with energies around 10^9 ev. Since it is now known that most of the particles with this energy are mesotrons, the ionization should correspond to that of electrons with $H\rho=10^9m/300\mu$, where μ and m are the masses of the mesotron and the electron, respectively. When this correction is made, Kunze's value of 19 ions/cm in normal air agrees with the minimum ionization found for electrons. C. T. R. Wilson[3] also counted primary ions in nine straight tracks of unknown energy which presumably were cosmic-ray mesotrons and obtained a value of 20 ions/cm. In the present experiment the primary ionization of both cosmic-ray electrons and mesotrons was measured.

---

[1] E. J. Williams and F. R. Terroux, Proc. Roy. Soc. **A126**, 289 (1930).
[2] H. K. Skramstad and D. L. Loughridge, Phys. Rev. **50**, 677 (1936).
[3] C. T. R. Wilson, Proc. Roy. Soc. **A104**, 192 (1923).
[4] P. Kunze, Zeits. f. Physik **83**, 1 (1933).