Townsend Ionization Coefficients and Uniform Field Breakdown in Hydrogen and Nitrogen at High Pressures*

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Values of α/p, the first Townsend coefficient divided by the pressure, reproducible to a few percent were measured in hydrogen and nitrogen by the standard Townsend procedure for the range of pressure p times electrode separation d of 100 to 800 mm Hg×cm. Values of α/p were obtained for the range of field strength to pressure ratio E/p of 14 to 22 and 30 to 45 volt cm^{-1} (mm Hg)$^{-1}$ in hydrogen and nitrogen, respectively. Current-voltage measurements at constant values of p and d taken to within 0.05% of the breakdown potential check the consistency of the α/p measurements and demonstrate the existence of the second Townsend coefficient γ for pd values as high as 750 in nitrogen and 800 in hydrogen. The primary multiplication at breakdown is only about 10^3 for both gases, and the existence of γ is necessary to account for total multiplications of 10^5 measured just below breakdown. The values of γ are reproducible to within about 20% for fixed values of p, d, and E/p, provided the nickel cathode used is not unduly abused by heavy currents. The values of γ are about 10^{-3} for values of E/p of about 20 in hydrogen and 40 in nitrogen, and were found to be unfalsified by space charge. Measured values of the breakdown potential in both gases are given within experimental error by the Townsend condition $\gamma(e^{\alpha d}-1)=1$. Variations of the state of the nickel cathode for both gases at constant p and d give rise to changes in both γ and the breakdown potential in accord with the Townsend condition. Alternately, values of the breakdown potential may be used with accurate values of α to obtain precise values of γ from the Townsend condition.

INTRODUCTION

UNTIL recently, it had been generally accepted that at values of products of pressure p and electrode separation d greater than 200 mm Hg×cm,[1] gas amplified currents in uniform dc fields up to breakdown follow the Townsend equation

$$I=I_0e^{\alpha d}, \quad (1)$$

where α is the first Townsend coefficient, I is the current in the gas, and I_0 is the initial electron current at the cathode.[2–4] Equation (1), which represents a current without a secondary mechanism, is inadequate to account for the phenomenon of breakdown, and failure to observe experimental deviations from this equation up to breakdown at $pd>200$ led, among other considerations, to the development of the streamer theory to account for breakdown in the high pd region.[5]

However, recent measurements of formative time lags of uniform field breakdown at low overvoltages in a number of gases at values of $pd>200$ indicate the existence of a secondary mechanism preceding breakdown.[6–8] This secondary mechanism was identified as photoelectric action at the cathode. In fact, a satisfactory equation for describing quantitatively the formative times of breakdown as a function of overvoltage was derived on the basis of such a secondary mechanism.[7] Furthermore, recent static ionization current measurements in air and in nitrogen at $pd\sim600$, using the standard Townsend method, indicated directly the existence of a secondary mechanism below breakdown by deviations from Eq. (1).[9] These measurements permitted some evaluations of the second Townsend coefficient γ from the equation

$$I=I_0e^{\alpha d}/[1-\gamma(e^{\alpha d}-1)]. \quad (2)$$

In the present work, prebreakdown currents in hydrogen[10] and nitrogen were measured with the purpose of verifying Eq. (2) at high pd with potentials as close to breakdown as practicable. An experimental procedure somewhat different from the standard one of Townsend, and having certain advantages over the latter method, was used for determining γ. In addition, the corresponding breakdown potentials were measured to test the Townsend breakdown condition. As a by-product of this work, self-consistent values of α/p for our gas samples were obtained.[11]

APPARATUS AND PROCEDURE

Unless otherwise noted, the apparatus used is essentially as previously described.[7] A thickness of ¼ inch of

* Supported by the Office of Naval Research. For a preliminary report of this work see Phys. Rev. **100**, 1227 (1955).

[1] The units of p and d are given in mm Hg and cm, respectively, throughout the paper; the unit of field strength E is given in volts/cm.

[2] L. B. Loeb and J. M. Meek, *The Mechanism of the Electric Spark* (Stanford University Press, Stanford, 1941), p. 29.

[3] L. B. Loeb, *Spark Breakdown in Uniform Fields* (Office of Naval Research, Department of the Navy, Washington, 1954), p. 69.

[4] L. B. Loeb, *Basic Processes of Gaseous Electronics* (University of California Press, Berkeley and Los Angeles, 1955), p. 751.

[5] J. M. Meek, Phys. Rev. **57**, 722 (1940); H. Raether, Arch. Elektrotech. **34**, 49 (1940); Z. Physik **117**, 375, 524 (1941). See also references 2 and 3.

[6] L. H. Fisher and B. Bederson, Phys. Rev. **75**, 1324, 1614 (1949); **81**, 109 (1951); H. W. Bandel, Phys. Rev. **95**, 1117 (1954); M. Menes, Phys. Rev. **98**, 561 (1955).

[7] G. A. Kachickas and L. H. Fisher, Phys. Rev. **88**, 878 (1952); **91**, 775 (1953).

[8] I. Lessin and L. H. Fisher, Phys. Rev. **93**, 649 (1954).

[9] F. Llewellyn Jones and A. B. Parker, Proc. Roy. Soc. (London) **A213**, 185 (1952); Dutton, Haydon, and Llewellyn Jones, Proc. Roy. Soc. (London) **A213**, 203 (1952).

[10] During the course of the present work, reports of measurements of γ (and α/p) in hydrogen were given by Wilkes, Hopwood, and Peacock, Nature **176**, 837 (1955), and by Crompton, Dutton, and Haydon, Nature **176**, 1079 (1955); Proc. Phys. Soc. (London) **B69**, 2 (1956).

[11] The values of α/p obtained for hydrogen during the course of the present experiments have been reported briefly by Rose, DeBitetto, and Fisher, Nature **177**, 945 (1956).

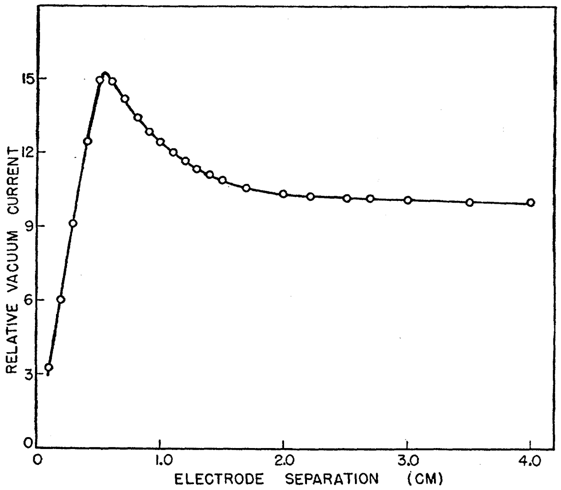

FIG. 1. Relative vacuum photoelectric current *vs* electrode separation at constant arc intensity.

the flat surface of the brass cathode was replaced by nickel. Gas currents were measured by means of a Keithley electrometer in parallel with Victoreen precision high resistors. By monitoring the output of the Hg arc lamp with a photocell, the initial illumination was kept constant to about 1%. The image of the arc on the cathode was about 10 cm^2, but this is a lower limit if the possibility of reflections of ultraviolet light from the anode and walls on to the cathode is considered. The photoemissivity of the cathode changed under bombardment by the larger dark currents measured ($\sim 10^{-6}$ amp) unless previously conditioned. This conditioning was accomplished by glowing at pressures of a few millimeters in the gas to be studied at a current of about 1 ma for a few hours. The cathode was illuminated only when a current measurement was being made in order to keep the effects of dark currents on the cathode to a minimum. Linde commercial tank hydrogen and Linde water pumped tank nitrogen were used.[12]

α was measured by the standard Townsend method of measuring the slope of a semilogarithmic plot of I *vs* d taken at constant I_0, p, and E below the region of d where γ is important. Measurements were taken at relatively high pd values to assure a high degree of accuracy in the α measurements; this required voltages up to 30 kv. As a result, the problem was encountered of measuring small currents with fluctuating voltages coupled into the electrometer system by means of the interelectrode capacitance. The effects of the fluctuations were eliminated by an electronic compensating device described elsewhere.[13]

In early runs made to determine α, the $\ln I$ *vs* d graphs were found to be very nonlinear for all values of d. It was found that I_0 changed appreciably with d at constant arc intensity even in vacuum. This is believed to be a consequence of sidewise illumination giving reflections from the walls and the movable anode on to the cathode. Figure 1 shows the relative vacuum current measured as a function of d at constant arc intensity at a constant E of about 100. When this correction is applied to the gas currents measured at each d, the previously nonlinear $\ln I$ *vs* d graphs are transformed to straight lines for both gases. This is illustrated for hydrogen in Fig. 2; the dashed lines represent the measured currents and the solid lines represent these currents corrected by means of Fig. 1 and not normalized in any other way. Measurements below $d=0.5$ were never taken because it was felt that the rapid decrease of I_0 below this value of d would lead to large inaccuracies in the corrected ionization currents; for this reason α was evaluated in each run for at least two and as many as four different values of E/p with the same arc intensity. This procedure helped to determine the slopes of the lines more accurately than if only one value of E/p had been studied in each run, since the lines must have a common intercept at the $d=0$ axis.

In both gases, a few values of α/p were also obtained by varying p at constant d, E/p, and I_0 as illustrated in Fig. 3 for hydrogen. In order to keep d constant during

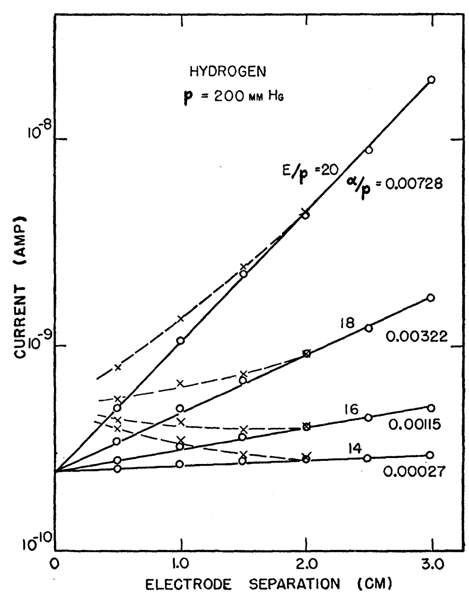

FIG. 2. Gas current *vs* electrode separation in hydrogen for various constant values of the ratio of field strength to pressure at 200 mm Hg. Dashed lines represent measured currents; solid lines represent measured currents corrected by means of Fig. 1. Resulting values of α/p are given at their respective values of E/p.

[12] Mass spectrographic analysis of the hydrogen and nitrogen were made through the courtesy of E. E. François of the Bell Telephone Laboratories. The hydrogen analysis yielded percentagewise: H_2—99.6; N_2—0.39; CO_2—0.005; A—0.005; H_2O—0.0007; the nitrogen analysis yielded percentagewise N_2—99.9; A—0.002; CO_2—0.002; CO—0.03; H_2O—0.005; NH_3—0.004; aliphatic hydrocarbons—0.002.

[13] D. J. DeBitetto, Rev. Sci. Instr. **26**, 986 (1955).

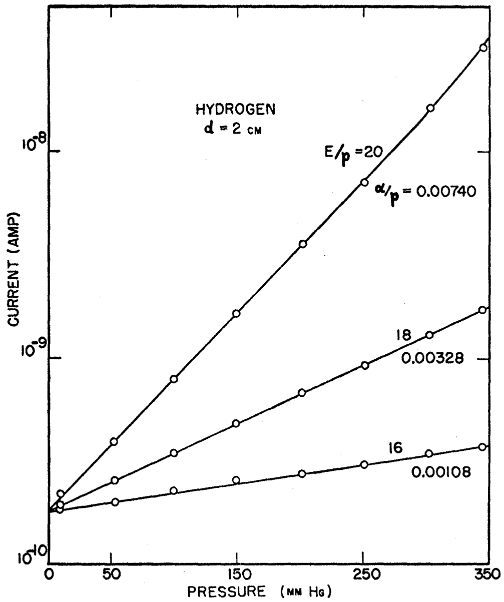

FIG. 3. Gas current *vs* pressure in hydrogen at constant electrode separation. The resulting values of α/p are given at their respective values of E/p.

these measurements, it was found necessary to readjust the electrodes at each pressure to compensate for changes in d (by at most 0.5%) caused by changes in internal pressure. The results of the two procedures are in good agreement for both gases, as is illustrated for hydrogen by the values of α/p given in Figs. 2 and 3 for corresponding values of E/p. This suggests that the technique of measuring α/p in chambers whose electrodes are fixed is a precision method worthy of exploitation.

Values of γ were obtained by the following procedure. For fixed values of p, d, and I_0, the voltage (and consequently E/p) was raised in steps to within 10 volts of breakdown while the corresponding currents were measured. Since it is possible to set voltage to one part in 10^4 while d cannot be set to better than one part in 10^3, using voltage as the independent variable instead of d as is used in the Townsend procedure allows a much closer approach to breakdown. In these close approaches to breakdown, it was found necessary to superimpose manual regulation of the voltage on the existing electronic regulation. Equation (1) is used with the measured values of α/p to give a value of I_0 at every current-voltage measurement in the voltage range where this equation is adequate. In the voltage range where Eq. (1) is inadequate, Eq. (2) may be used to calculate values of γ using the previously measured values of α/p and an average value of I_0 obtained in the same run.

The effects of field distortion due to geometric factors were minimized by working at separations such that sparks (confined filamentary discharges) when allowed to occur always passed in the uniform region of the gap.

All measurements have been corrected to 22°C.

EXPERIMENTAL RESULTS AND DISCUSSION

Figures 4 and 5 show the results of the present α/p measurements in the E/p region of 14 to 22 in hydrogen and 30 to 45 in nitrogen, respectively; for comparison, the results of some other workers are also included.[14] As may be seen from Fig. 4, a single curve is sufficient to describe the α/p observations in hydrogen of Wilkes, Hopwood, and Peacock,[10] Rose,[11] and the present authors in this E/p range, while the observations of Crompton, Dutton, and Haydon[10] are larger. As is seen in Fig. 5, the situation in nitrogen is not as satisfactory for the E/p range shown. Some of our points in both gases represent average values obtained by repeating runs as many as four times with different gas samples at different pressures; all values obtained were reproducible to within a few percent.

We now proceed to a discussion of the γ measurements. Figure 6 shows a typical current-voltage curve for hydrogen at $p=400$ and $d=2$; such a series of measurements will be called a γ run. Actually each point in Fig. 6 is the average of two measurements, one obtained with increasing voltage and the other with decreasing voltage. With increasing voltage, current-voltage measurements were discontinued when the curve became almost vertical, and about ten determinations of the

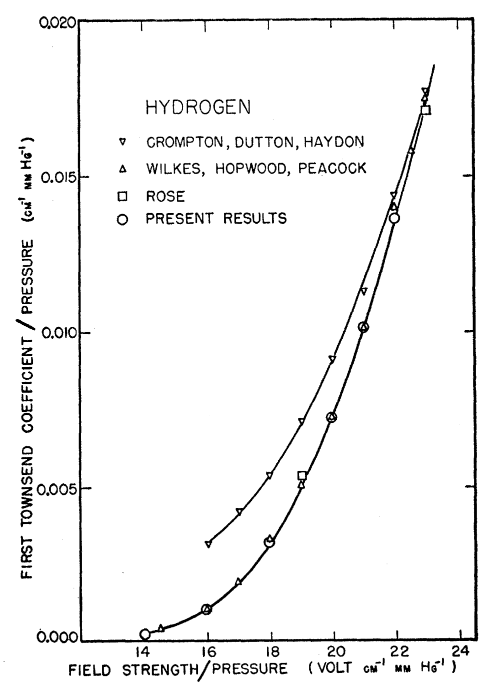

FIG. 4. α/p *vs* E/p for hydrogen.

[14] K. Masch, Arch. Elektrotech. **26**, 587 (1932); D. Q. Posin, Phys. Rev. **50**, 650 (1936). See also references 9, 10, and 11.

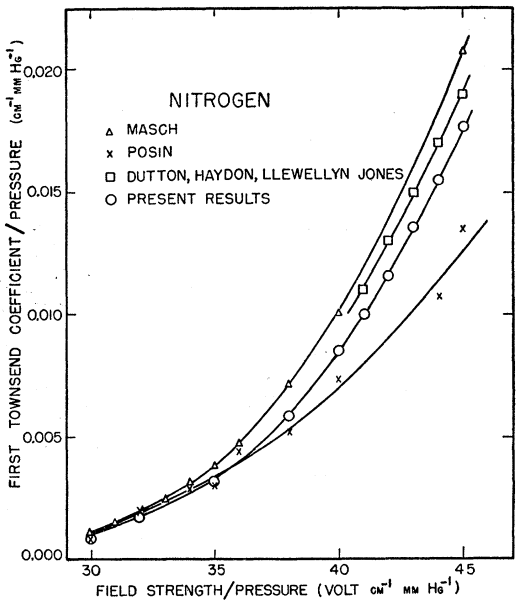

FIG. 5. α/p *vs* E/p for nitrogen.

breakdown potential V_B were then made with I_0 due to background alone. The spread in the observed values of V_B for any one run is about four volts; the average value of V_B for a run will be denoted by $\langle V_B\rangle_{Av}$.[15] Occasionally a spark was allowed to pass. After $\langle V_B\rangle_{Av}$ was determined, the second half of the run was made with decreasing voltage. Figure 7 shows the data of Fig. 6 replotted where the ordinate is the measured current divided by $e^{\alpha d}$, the latter quantity being obtained from our α/p measurements. The initial horizontal section of the curve in Fig. 7 demonstrates the self-consistency of the α/p measurements. The average values of I_0 ($\langle I_0\rangle_{Av}$) for the increasing and decreasing legs of this particular γ run were 2.93×10^{-10} and 2.62×10^{-10} amp, respectively, showing a decrease in the photosensitivity of the surface of ten percent. Each current-voltage measurement within two percent of breakdown was used to calculate a value of γ from Eq. (2) (using the value of $\langle I_0\rangle_{Av}$ corresponding to the leg of the run in which the measurement was made). The important range wherein self-consistent values of γ were obtained with the present equipment, where $\gamma(e^{\alpha d}-1)$ is between 0.5 and unity, occurs within about 2% of breakdown for the values of pd studied; the voltage control in the present work permitted an approach to within 0.05% of breakdown. The average values of γ ($\langle\gamma\rangle_{Av}$) so obtained from the γ run of Fig. 6 (spreads in γ will be discussed later) were 1.21×10^{-3} and 1.25×10^{-3} for the increasing and decreasing legs of the run, respectively, for an average E/p ($\langle E/p\rangle_{Av}$) of 20.3.[16] Figure 8 shows a curve for nitrogen similar to Fig. 7 for $p=300$, $d=2$ with an $\langle I_0\rangle_{Av}$ of 6.5×10^{-13} amp from which self-consistent values of γ were also obtained. Figure 8 was obtained from a curve similar to that shown in Fig. 6; this particular γ run in nitrogen yielded values of $\langle\gamma\rangle_{Av}$ of 1.43×10^{-3} and 1.37×10^{-3} for the increasing and decreasing legs of the run, respectively, for an $\langle E/p\rangle_{Av}$ of 41.7. As is illustrated by the above results, values of γ for both gases do not change appreciably as the result of the heavy breakdown glow currents and a spark or two. The above results are typical of all γ runs made; almost all of the γ runs were made at $p=400$, $d=2$ in hydrogen and at $p=300$, $d=2$ in nitrogen. γ runs made at other values of p and d will

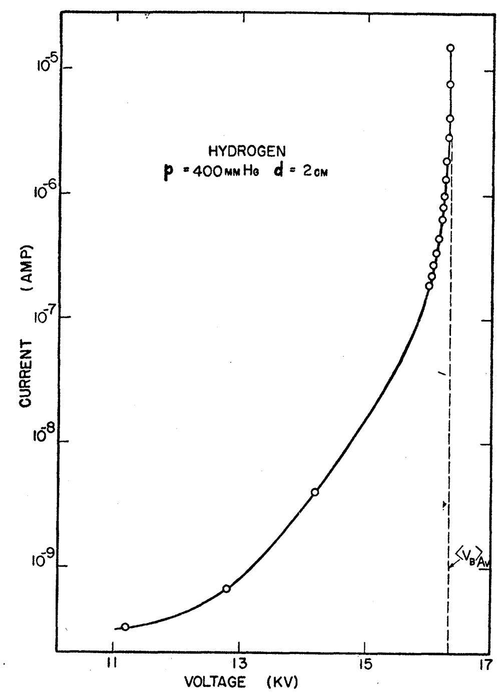

FIG. 6. Measured gas current *vs* voltage for hydrogen at constant electrode separation, pressure, and initial current. The breakdown potential (16 332 v) is given by the vertical dashed line $\langle V_B\rangle_{Av}$.

[15] With the experimental equipment used, the first evidence of a luminous discharge throughout the work in both gases was not the commonly reported filamentary spark (hereafter referred to simply as a spark) but a visible glow, sometimes covering the anode, and sometimes completely filling the gap. These glows have been previously observed in nitrogen[7] and hydrogen [I. Lessin, Ph. D. thesis, New York University, 1953 (unpublished)]. The visible glows have been found in the present work to be associated with self-sustained currents of the order of 1 μa. These self-sustained currents and glows were found to be steady in nitrogen but fluctuated in hydrogen; these phenomena are presently under investigation. It appears that the threshold voltages for the appearance of the glow (which we call V_B) and the spark are very close.

[16] Since values of $\langle\gamma\rangle_{Av}$ for any one γ run in this work were obtained from individual γ values (usually 25 in number) at slightly different individual values of E/p, wherever a value of $\langle\gamma\rangle_{Av}$ is given, the average of the corresponding values of E/p ($\langle E/p\rangle_{Av}$) is also given. Throughout the paper, $\langle\gamma\rangle_{Av}$ (and $\langle I_0\rangle_{Av}$) may either refer to the average value of γ (and I_0) over a leg of a single run or over both legs of a single run, depending on which is more appropriate. The average values of $\langle\gamma\rangle_{Av}$, $\langle I_0\rangle_{Av}$, and $\langle V_B\rangle_{Av}$ for more than one run will be denoted by $\langle\gamma\rangle_{Av}^*$, $\langle I_0\rangle_{Av}^*$, and $\langle V_B\rangle_{Av}^*$, respectively.

be discussed later. As will be seen, the values of γ are not falsified by space charge distortion.

Distribution "A" in Fig. 9 represents a typical distribution[17] of 102 γ values for hydrogen obtained by the method outlined above in four γ runs in the same gas sample at about the same value of $\langle E/p\rangle_{Av}$ (20.3) at $p=400$, $d=2$. The condition of the cathode throughout this series of runs was reasonably constant as was indicated by the values of $\langle I_0\rangle_{Av}$ and $\langle\gamma\rangle_{Av}$ obtained. The value of $\langle\gamma\rangle_{Av}^*$ of the distribution is 1.07×10^{-3}, the distribution showing a half-width of 14%. For these runs, the value of $\langle V_B\rangle_{Av}^*$ is 16 364 volts and the maximum spread in $\langle V_B\rangle_{Av}$ from run to run is 20 volts. Figure 10 represents the distribution of 55 values of γ

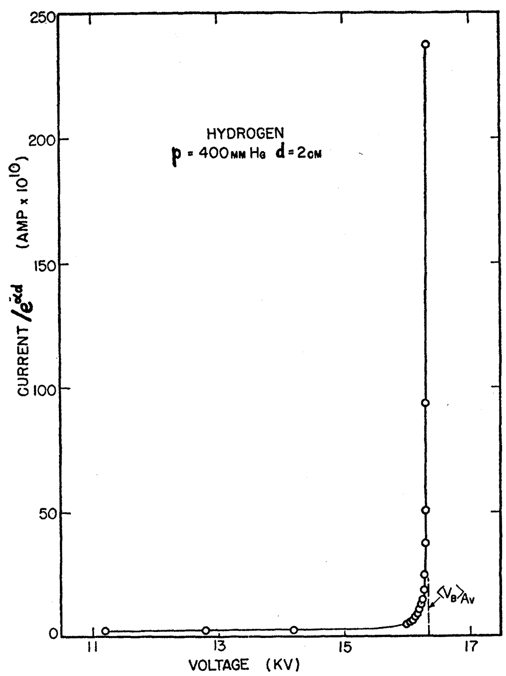

FIG. 7. Measured gas current of Fig. 6 divided by $e^{\alpha d}$ plotted against voltage. The breakdown potential is given by the vertical dashed line $\langle V_B\rangle_{Av}$. Resulting average value of second Townsend coefficient for this run is 1.23×10^{-3}.

for nitrogen obtained in three typical γ runs at an $\langle E/p\rangle_{Av}$ of about 41.7 in different samples of gas at $p=300$, $d=2$. The value of $\langle\gamma\rangle_{Av}^*$ for Fig. 10 is 9.20×10^{-4}, the distribution showing a half-width of 20%. For the runs of Fig. 10, the value of $\langle V_B\rangle_{Av}^*$ is 25 165 volts, and the maximum spread in $\langle V_B\rangle_{Av}$ is 45 volts. This test for reproducibility of γ in both gases was required to make meaningful the subsequent investigation of the variation of the second Townsend coefficient with E/p and with changes in the state of the cathode now to be described.

The variation of $\langle\gamma\rangle_{Av}$ with $\langle E/p\rangle_{Av}$ was investigated

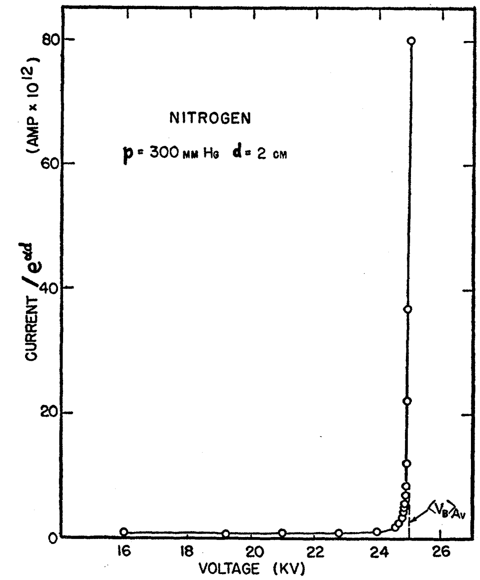

FIG. 8. Measured gas current divided by $e^{\alpha d}$ *vs* voltage for nitrogen at constant electrode separation, pressure, and initial current. The breakdown potential (24 990 v) is given by the vertical dashed line $\langle V_B\rangle_{Av}$. The resulting average value of the second Townsend coefficient for this run is 1.40×10^{-3}.

in both gases in the following manner. In hydrogen, a γ run was made at an $\langle E/p\rangle_{Av}$ of 20.3 ($p=400$, $d=2$). Some gas was then pumped out and another γ run was made immediately in the residual gas at an $\langle E/p\rangle_{Av}$ of 21.2 ($p=300$, $d=2$). The value of $\langle\gamma\rangle_{Av}$ at the higher value of $\langle E/p\rangle_{Av}$ was larger than that obtained at the lower value of $\langle E/p\rangle_{Av}$. To make certain that the cathode had not changed throughout the above measurements, a new hydrogen sample was admitted to $p=400$ ($d=2$) immediately after the $p=300$, $d=2$ run, and a γ run was made again at $\langle E/p\rangle_{Av}=20.3$. This entire procedure was carried out half a dozen times for the same values of p and d at widely different times with different states of the nickel cathode for about the same values of $\langle E/p\rangle_{Av}$. The two values of $\langle\gamma\rangle_{Av}$ made at

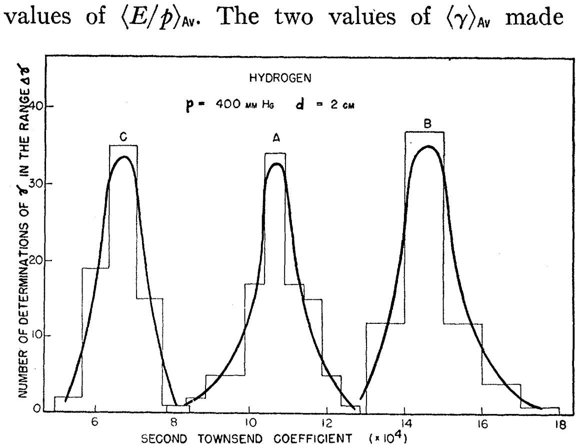

FIG. 9. Distribution of γ values obtained in hydrogen at constant pressure and electrode separation for three different states of the nickel cathode.

[17] In Fig. 9 (as well as in Fig. 10) the histograms represent the observed frequency distributions; the smooth curves have been freely drawn to represent the corresponding distribution curves.

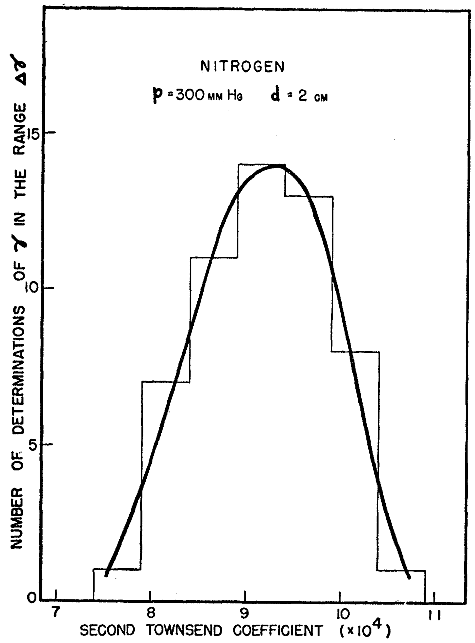

FIG. 10. Distribution curve of γ values obtained in nitrogen at constant pressure and electrode separation for a number of runs in different gas samples.

$\langle E/p\rangle_{Av}\cong 20.3$ at any one time showed a spread of at most and often less than 13%. However, the values of $\langle\gamma\rangle_{Av}$ obtained at $\langle E/p\rangle_{Av}\cong 21.2$ were always higher, on the average by 24%, than those obtained at $\langle E/p\rangle_{Av}\cong 20.3$. Since this represented a rather large variation in $\langle\gamma\rangle_{Av}$ with $\langle E/p\rangle_{Av}$, two of the above sets of γ runs were immediately extended to include γ runs at $\langle E/p\rangle_{Av}\cong 25.1$ ($p=100$, $d=2$) to check this rapid change.[18] The resulting value of $\langle\gamma\rangle_{Av}^*$ at $\langle E/p\rangle_{Av}\cong 25.1$ was 2.24 times that obtained at $\langle E/p\rangle_{Av}\cong 20.3$, in accord with the variation previously found between $\langle E/p\rangle_{Av}$ of 20.3 and 21.2. It is concluded that the second Townsend coefficient in hydrogen varies by about a factor of two with a 25% change in E/p in this range. Hence distribution "A" of Fig. 9 should have at least a natural breadth of about 10% resulting from the present method of measuring γ values by varying E/p over a 2% range in any one run. The variation of $\langle\gamma\rangle_{Av}$ with $\langle E/p\rangle_{Av}$ was not studied as extensively in nitrogen as in hydrogen. Two successive γ runs in nitrogen at $\langle E/p\rangle_{Av}$ of 41.7 ($p=300$, $d=2$) yielded a value of $\langle\gamma\rangle_{Av}^*$ of 9.12×10^{-4}. The pressure was then reduced to $p=200$ ($d=2$, same gas sample) and a γ run at $\langle E/p\rangle_{Av}$ of 44.5 yielded $\langle\gamma\rangle_{Av}=10.1\times 10^{-4}$; a new gas sample at $p=300$, $d=2$ gave $\langle\gamma\rangle_{Av}=9.35\times 10^{-4}$ at $\langle E/p\rangle_{Av}=41.7$. The electrode separation was increased to 2.5 cm ($pd=750$) and a γ run was made at $\langle E/p\rangle_{Av}=40.3$ whose resulting value of $\langle\gamma\rangle_{Av}$ was 1.05×10^{-3}. The indications are that the second Townsend coefficient is an insensitive function of E/p in nitrogen in this range. The values of $\langle I_0\rangle_{Av}$ for the above runs were about 10^{-10} and 10^{-12} amp for hydrogen and nitrogen, respectively.

To investigate the possibility of the falsification of the experimental values of γ by space charge distortion of the field, it was desired to change the initial current density J_0 by some large factor. After a γ run with a value of $\langle I_0\rangle_{Av}$ of about 10^{-10} amp in hydrogen at $p=400$, $d=2$, $\langle I_0\rangle_{Av}$ was reduced by a glass filter by an order of magnitude, and another γ run was made in the same gas sample. The two values of $\langle\gamma\rangle_{Av}$ so obtained agreed to within two percent. The above conclusion was verified by repeating this experiment at a later time and with a different state of the nickel cathode. In nitrogen, it was decided to study the effect of space charge on γ by changing I_0 (and J_0) by two orders of magnitude. However, decreasing I_0 from 10^{-12} amp in nitrogen led to currents too small to measure conveniently; it was found possible to first increase the photoelectric sensitivity of the surface (by glowing in hydrogen at low pressure and then outgassing at $p\leqslant 10^{-3}$ for a period of two weeks). With the resulting surface of improved photosensitivity, and with values of $\langle I_0\rangle_{Av}$ of about 10^{-10} and a reduced $\langle I_0\rangle_{Av}$ of about 10^{-12} amp, two γ runs were made in nitrogen. The values of $\langle\gamma\rangle_{Av}$ so obtained with the two values of $\langle I_0\rangle_{Av}$ agreed with each other to within four percent, although the value of $\langle\gamma\rangle_{Av}^*$ for these two runs was about 50% higher than the value obtained with the original surface ($\langle\gamma\rangle_{Av}^*$ of Fig. 10). For a given ultraviolet flux incident on both the original and photosensitized cathodes, $\langle I_0\rangle_{Av}$ for the photosensitive surface was about four times that of the surface used to obtain Fig. 10. Thus increasing the photosensitivity of the nickel cathode in nitrogen increases the value of the second Townsend coefficient somewhat. $\langle V_B\rangle_{Av}$ for these two runs in nitrogen with the photosensitive cathode agreed to within 40 volts of each other, and the resulting $\langle V_B\rangle_{Av}^*$ was 195 volts lower than the value of $\langle V_B\rangle_{Av}^*$ of Fig. 10 obtained with the less photosensitive cathode. The photosensitive cathode was then further conditioned by allowing heavy breakdown glow currents ($\sim 10^{-5}$ amp) to pass in the same gas sample at high pressure, and it was found that the cathode photoemissivity was slowly reduced to about 1.5 times the value of the original cathode of Fig. 10. With this resulting surface of decreased photosensitivity, another γ run was carried out yielding a $\langle\gamma\rangle_{Av}$ differing from the $\langle\gamma\rangle_{Av}^*$ of Fig. 10 by only three percent. $\langle V_B\rangle_{Av}$ for this last run agreed with the value of $\langle V_B\rangle_{Av}^*$ of Fig. 10 to within 35 volts. Thus these experiments in nitrogen not only demonstrate the absence of space charge effects on the second Townsend coefficient in the present experiment, but also show the dependency of the second Townsend coefficient and the breakdown potential on the nature of the cathode. Since all meas-

[18] Since the values of α/p in the present work were obtained for values of $E/p\leqslant 22.0$, extrapolation of the α/p *vs* E/p curve was required to $E/p\cong 25.1$ to enable calculation of γ values for the $p=100$, $d=2$ runs. Use of the extrapolated curve to E/p of 25.1 is justified by the excellent agreement so obtained with the α/p measurements of Wilkes, Hopwood, and Peacock[10] and Rose.[11]

urements reported in this paper were made with values of I_0 of about 10^{-10} amp or less, it is concluded that space charge effects on all results are negligible.

The dependency of the second Townsend coefficient and the breakdown potential on the state of the cathode was studied in hydrogen in a more detailed fashion; relatively large changes of the state of the nickel cathode were obtained by low pressure high current glowing. As soon as the γ runs giving rise to distribution "A" in Fig. 9 were completed, the gas was pumped out and the chamber was glowed in hydrogen at 1.50 mm at 0.1 ma for 1.5 hours. After flushing and refilling the chamber with hydrogen to a pressure of 400 ($d=2$), two γ runs were taken whose resulting value of $\langle\gamma\rangle_{Av}^*$ was 38% higher than that of distribution "A" of Fig. 9, and whose $\langle V_B\rangle_{Av}^*$ was 100 volts lower than that corresponding to distribution "A" of Fig. 9. The resulting distribution of the 66 determinations of γ made in these last two γ runs is given as distribution "B" in Fig. 9. The hydrogen was then removed, and the electrodes were conditioned by glowing in seven mm of dry air at 70 μa for one half hour. After flushing and refilling with hydrogen to 400 mm ($d=2$), three γ runs then yielded a value of $\langle\gamma\rangle_{Av}^*$ which was about 55% less than the previously determined $\langle\gamma\rangle_{Av}^*$ of distribution "B" with a corresponding increase of $\langle V_B\rangle_{Av}^*$ of 260 volts. The resulting distribution of the 72 evaluations of γ made in these last three runs is given as distribution "C" in Fig. 9. The average half-width of these three distributions is about 15%. Throughout the measurements leading to the three distribution curves of Fig. 9, the electrode separation was not readjusted. The values of $\langle I_0\rangle_{Av}^*\times 10^{11}$ for distributions "B," "A," and "C" are 46, 14, and 4.8, respectively, while the corresponding ratio of the values of $\langle\gamma\rangle_{Av}^*$ is 2.20/1.58/1.00, respectively. These results indicate a rough correlation of the second Townsend coefficient in hydrogen with the photoemissivity of the cathode. Figure 9 shows quite clearly in distribution form the cathode dependency of the second Townsend coefficient (and consequently the breakdown potential) in hydrogen at $p=400$, $d=2$. It is concluded from the present studies in hydrogen with various conditions of the cathode that the breakdown potential in hydrogen at high pd, just as in nitrogen, depends on the nature of the cathode. It is also clear that values of standard breakdown potentials will eventually have to specify the nature and condition of the cathode at large values of pd.

Therefore, it is quite impossible to take the measurements of γ of one experimenter and apply them with confidence to the surface of another even though both are using electrodes of the same material. Even a single experimenter will have to convince himself that his own values of γ are being applied to a surface in the same state for which the values of γ were obtained. For this reason, detailed comparison of our values of γ with those of other observers is not particularly meaningful. However, the values of γ obtained recently by other workers in hydrogen and nitrogen are of the same order of magnitude as obtained in the present work.[9,10]

The effect of sparking on γ was investigated in hydrogen by passing 140 sparks at $p=400$, $d=2$; the value of $\langle\gamma\rangle_{Av}$ measured in a γ run following these sparks was within three percent of the value measured in a γ run before the sparks in the same gas sample, although the photoemissivity of the cathode was found to have increased by about 25%. Thus it appears that heavy pre-breakdown currents spread out over the whole discharge volume change the nature of the cathode in hydrogen more effectively than the passage of a considerable number of localized sparks with our circuit.

Since in all runs made in determining γ, breakdown potentials were also measured, it was possible to see if the Townsend condition $\gamma(e^{\alpha d}-1)=1$ is fulfilled at breakdown. The average of all values of $\gamma(e^{\alpha d}-1)$ at breakdown is 1.018 for hydrogen, and 0.975 for nitrogen. If $\gamma(e^{\alpha d}-1)$ is set equal to unity for either of these gases and the resulting breakdown potential is calculated from the measured value of α/p and the value of $\langle\gamma\rangle_{Av}$ obtained from a single run, the breakdown potential agrees with the experimentally determined $\langle V_B\rangle_{Av}$ for the same run to within a few tenths of a percent. Alternately, $\langle V_B\rangle_{Av}$ for a run may be used with accurately known α/p values to determine a value of γ which agrees with the experimentally determined value of $\langle\gamma\rangle_{Av}$.

All γ runs discussed so far (with the exception of one in nitrogen) were made with $d=2$. Further experiments were made to determine whether the second Townsend coefficient is independent of d at constant pd and at approximately constant E/p. In nitrogen, values of γ were deduced (by means of the Townsend breakdown condition from values of α/p and measured values of $\langle V_B\rangle_{Av}$) for $pd=600$ at values of d varying from 1 to 4 cm. The resulting values of γ were in good agreement and showed no systematic variation. On the other hand, a similar study in hydrogen for the same value of pd over the same range of d yielded values of the second Townsend coefficient which increase with increasing d. Several γ runs in hydrogen verified this variation. Thus two γ runs in hydrogen yielded $\langle\gamma\rangle_{Av}$ of 4.89×10^{-4} for $p=600$, $d=1$ and $\langle\gamma\rangle_{Av}$ of 9.95×10^{-4} for $p=300$, $d=2$ in the same gas sample. The cause of this variation of γ with d at constant pd in hydrogen is not clear at the present time. The variation cannot be due to geometric field distortion or the same effect would have been observed in nitrogen. Regardless of the reason for the variation of γ and V_B with d at constant pd in hydrogen, the value of V_B and the corresponding value of γ obtained by extrapolating the $\langle V_B\rangle_{Av}$ *vs* d curve to $d=0$ should be representative of the ideal values for infinite plane parallel electrodes. Thus all the values of γ for hydrogen given in this paper at $d=2$ may be corrected to ideal values by dividing by a factor of 2.4. Since variations in the state of the cathode may give rise to a variation in γ by a factor of two, the variation of γ with d at constant pd cannot be considered any more important than the state of the cathode in determining absolute values of the second Townsend coefficient. It is interesting to note that even though the measured values of γ in hydrogen depend on d, the Townsend condition for breakdown holds at any separation providing the value of γ inserted into the condition is measured at the corresponding value of d.

For both gases, the value of $e^{\alpha d}$ at breakdown is of the order of 10^3, and at 2% overvoltage is only of the order of 2×10^3. In the present work total multiplications of 10^5 (due to first and second ionization coefficients acting simultaneously) have been measured below breakdown. To attain this multiplication of 10^5 by a primary ionization process alone would require an overvoltage of about ten percent. In formative time lag work, two percent overvoltage in these gases has been shown to lead to a spark within a fraction of a microsecond.[7,8] Hence, it is concluded that a secondary mechanism is necessary not only to describe prebreakdown currents but is also necessary to describe the buildup process preceding a spark up to overvoltages of the order of 10% in these gases.

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Čerenkov Radiation of Neutral Particles with a Magnetic Moment*

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A simple expression is deduced for the Čerenkov radiation caused by magnetic and electric dipoles. The effect is very small. In the visible spectrum for a fast neutron, the energy loss per unit path per unit frequency range is about 10^{-15} times that of a fast electron. The expression for the energy loss does not contain explicitly the mass of the moving particle. Consequently, this method cannot be used to try to detect whether or not the neutrino has any trace of a magnetic moment.

I

In this note we shall discuss the radiation caused by neutral particles endowed with a magnetic moment, which move through matter. As in the discussion of Čerenkov radiation, we shall be interested in the case when the velocity of the particle is constant, and exceeds that of light in the medium. Though it turns out that the effect is too small to be observed, we think the results are of interest.[1]

In Sec. II we give a rather intuitive derivation of the energy radiated per unit path length. In Sec. III we derive this expression from Maxwell's equations. In Sec. IV we give a brief numerical estimate.

II

If an electron moves with the constant velocity $v>c/n$, through a medium of index of refraction n, the energy lost per unit path length by radiation with frequency between ω and $\omega+d\omega$ will be given by[2]:

$$(e^2/n^2)(\beta^2n^2-1)(\omega/v)d\omega/v, \quad (\beta=v/c). \tag{1}$$

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[1] After completion of this work, my attention has been called to a paper by V. L. Ginsburg, J. Phys. (U.S.S.R.) 2, 441 (1940). In this article the author quotes the results of his calculations (by a different method) concerning this effect. His results are identical with ours for a dipole if the dipole axis is parallel to the direction of motion, but differ from ours if the axis is normal to it. Though Ginsburg does not give details, one suspects an error, since according to his expression the radiated energy would be proportional to the dipole moment and not to its square.

[2] See, e.g., L. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1949), p. 265.

We pose now the question: Can one derive from Eq. (1) by some simple intuitive manipulation the energy loss per unit path length for an electric dipole moving under similar conditions? (If one is able to do this for an electric dipole, one can do it immediately for a magnetic dipole as well.) The answer is yes.

For, observe first that (1) contains the time average of the Poynting vector, integrated over a surface. The Poynting vector in turn contains products of the field strengths. Now we can obtain the field of a dipole by taking the space derivatives of the field of a charge and multiply it by, say, q, the separation of the charge in the dipole. Now, in the expression for the field of the charge each coordinate will appear, for dimensional reasons, multiplied by a characteristic length s. Hence each operation on the field will bring in a factor q/s. Since the whole physical situation is stationary, (q/s) will be a constant, and will not be influenced by the time averaging. Thus we expect that (1), containing the products of fields, will acquire a factor $(q/s)^2$. Also, if the dipole is directed normal to the direction of motion, we expect the field to have an angular dependence $\cos\varphi$ and $\sin\varphi$ (φ being an angle in a plane normal to the direction of motion). The squares of this factor, averaged, will bring in another factor $\frac{1}{2}$. Let us find now s, the characteristic length. We expect that this will be the distance the electron has to travel (as seen by the electron) to emit a wave of frequency ω. The time to emit one wave of frequency ω is $1/\omega$; however, for the electron this duration will change into $1/[\omega(\beta^2n^2-1)^{\frac{1}{2}}]$