PHYSICAL REVIEW VOLUME 98, NUMBER 2 APRIL 15, 1955

Mechanism of the Termination of the Geiger Plateau Region*

H. L. WISER AND A. D. KRUMBEIN
Physics Department, University of Maryland, College Park, Maryland

(Received November 8, 1954)

The mechanisms responsible for the termination of the Geiger counter plateau region at its high-voltage end were investigated by a direct experimental method. Geiger counters were operated in a normal manner and counting rate *versus* voltage and number of positive ions per pulse *versus* voltage were measured in the breakdown region. Analysis of the data indicated that spurious counts could result from two phenomena: (1) Secondary electrons created by positive-ion bombardment of the cathode; and (2) metastable atom and molecule decay in the gas. The rate of spurious counts caused by positive-ion bombardment was found to be proportional to the rate of positive ions striking the cathode and, therefore, proportional to the voltage. This accounted for the plateau slope, if present, and the slight increase in slope at the beginning of the breakdown region. It is shown that the exponential rise in counting rate in the breakdown region can be explained by the decay of metastable atoms and molecules that exist after the deadtime of the primary pulses. Experimental results indicate that metastable atoms were dominantly responsible for spurious counts at low pressures (about 40 mm Hg) and metastable molecules at high pressures (200 mm Hg).

I. INTRODUCTION

SPURIOUS pulses in Geiger counters conceivably may be caused by positive ions, negative ions, or photons. The theory of positive-ion bombardment of the cathode as a source of spurious counts has been presented by Korff and Present.[1] However, their theory could not explain the relatively sudden onset of spurious counts with the increase of applied voltage. Willard and Montgomery's explanation that spurious counts were caused by negative ions could not be accepted for the breakdown region where the counting rate was rapid.[2] Colli and Facchini reported photon bombardment of the cathode to be responsible for the continuous discharges seen in their counters.[3] Their counters, however, had no plateau region and were operated at voltages that would have been well above the start of the breakdown region had there been plateaus. DuToit conducted two different experiments in an attempt to settle the controversy, but his results were indecisive, one experiment favoring the positive-ion theory and the second favoring the photon theory.[4] In the present study a direct experimental approach was used for the purpose of allowing the experiment itself to provide data to resolve this dilemma. Geiger counters were operated in a normal manner and counting rate *versus* voltage and number of positive ions per pulse *versus* voltage were determined in the breakdown region at small increments of applied voltage.

II. APPARATUS AND EXPERIMENTAL PROCEDURE

Demountable counters were used throughout. The whole counter, shown in Fig. 1, was encased in an evacuated glass chamber and filled with appropriate gases at the desired pressures. The cathodes, shown in Fig. 2, were designed so as to maintain the same surfaces for various radii, thereby eliminating surface structure as a variable parameter. This had been a parameter of unknown behavior responsible for discrepancies in the results of different experimenters.[5] A width of brass sheet (0.002 in. thick) was cut to equal the circumference of the largest of the desired cathodes, so that, when rolled into a cylinder, the springy brass held itself firmly against the inside of a glass tube of equal circumference, forming a closed metal surface.

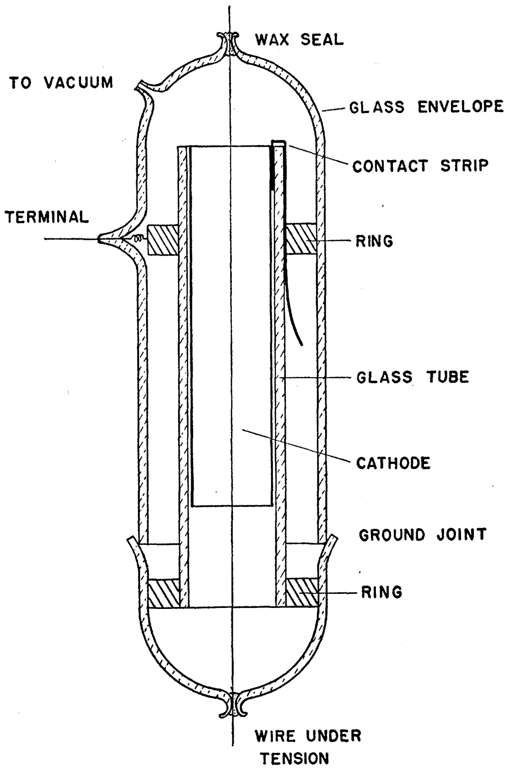

FIG. 1. Geiger counter assembly.

---

* Supported by U. S. Bureau of Ships. The information contained in this paper is part of a thesis submitted by one of the authors, H. L. Wiser, in partial fulfillment of the requirements for the Ph.D. degree at the University of Maryland.

[1] S. A. Korff and R. D. Present, Phys. Rev. **65**, 274 (1944).

[2] D. Willard and C. G. Montgomery, Rev. Sci. Instr. **21**, 520 (1950).

[3] L. Colli and U. Facchini, Phys. Rev. **88**, 987 (1952).

[4] S. J. DuToit, Phys. Rev. **73**, 1473 (1948).

[5] L. B. Loeb, *Fundamental Processes of Electrical Discharges in Gases* (John Wiley and Sons, Inc., New York, 1939), p. 378.

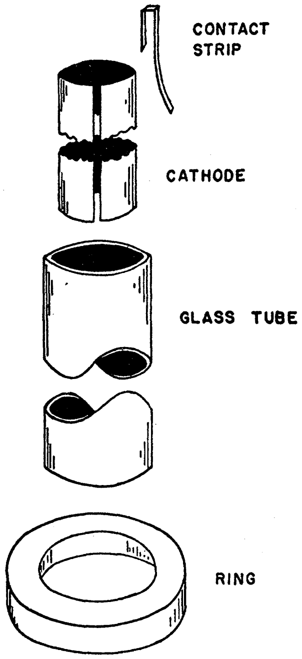

FIG. 2. Cathode assembly.

When the counters were disassembled for experiments with smaller cathode radii, the same piece of brass sheet was cut to fit the inner diameter of the next smaller glass tube. This process was continued for subsequent runs with still smaller cathode radii.

The tungsten anode wires, which were 3, 4, or 8 mils in diameter, were changed after only two or three runs because their surfaces were damaged by the intense electron bombardment, giving rise to erratic counter behavior and nonreproducible results in the breakdown region.

Each experimental run was preceded by the cleaning, evacuating, and filling of the Geiger counters. The vacuum system of conventional design was evacuated for a minimum of 10 hours at pressures less than 0.001 mm Hg. The system then remained static for several hours, and a change in pressure no larger than 0.001 mm Hg was an indication of sufficient outgassing.

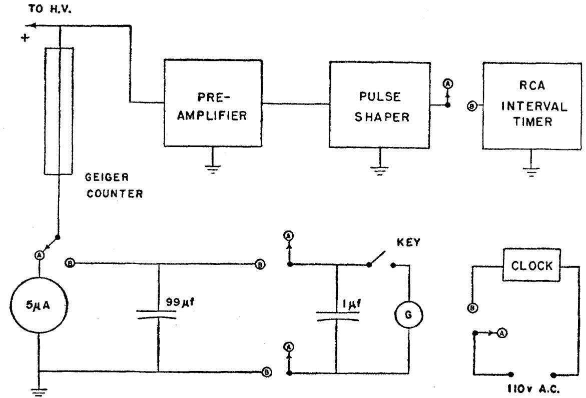

FIG. 3. Block diagram of the experimental arrangement.

Quenching vapor was then admitted to the counter manifold system to the desired pressure, which ranged from 2 to 20 mm Hg. Spectroscopically pure argon gas was introduced into the counters until the desired total pressure was attained. The counters were not used for about an hour after being filled, allowing quenching and vehicle gases to mix uniformly throughout the volume of the counters.

The high-voltage supply design given by Strong served as the basis for the circuit employed.[6] His circuit and component values were modified slightly to produce a regulated, stabilized voltage of 2000 volts with a drift of less than half a volt per hour. The error in voltage reading was less than 0.1 percent.

Spurious pulses in the breakdown region were of random height, mostly smaller than the primary pulse, and occurred at randomly rapid rates. Since the time interval between pulses was an important factor in counting all pulses, an RCA interval timer capable of counting pulses separated by as little as 1 microsecond was used. An ordinary preamplifier and pulse-shaping circuit converted the Geiger counter pulses to the required pulse height and rise time necessary to trigger the interval timer.

The number of ions per pulse could not be measured directly; therefore the average number of ions per pulse was measured instead. The simplest method was to store charge equal to the charge of the ions as they were collected at the cathode. This was performed by a bank of condensers placed between the cathode of the counter and ground. A bank of condensers totalling 100 microfarads was used inasmuch as it was not desirable to have a voltage drop across the condensers greater than 0.5 volt.

The system of switches, schematized as part of the complete operating circuit in Fig. 3, was designed to synchronize the time interval, pulses counted, and charge collected for a given period of data collection. The systems were coordinated to act simultaneously with an error of less than 0.01 second. The coordinated apparatus were the register, the stopwatch, the condenser bank, and an auxiliary current meter in parallel with the condenser bank. Four switches were operated simultaneously by one master lever. An electric stopwatch recorded the total time interval to within a tenth of a second.

Termination of the breakdown region was signified by three factors: (a) extremely rapid counting at a continuous rate even with the radioactive source removed; (b) arcing inside the counter between the electrodes, visible if the laboratory was darkened; and (c) an increasing current through the 5-μa microammeter driving the needle of the meter off scale.

Four types of data were tabulated: (a) counts

---

[6] J. Strong, *Procedures in Experimental Physics* (Prentice-Hall, Inc., New York, 1946), p. 296.

recorded; (b) time of counting interval; (c) total charge collected in the counting interval; and (d) applied voltage.

From these data, plots were made of counting rate *versus* voltage and average number of ions per pulse *versus* voltage.

III. RESULTS

(a) Counting Rate *versus* Voltage

The characteristic plot of Geiger counter operation, counting rate *versus* voltage, is shown in Fig. 4. This plot established the plateau region in which the counting rate was constant with increasing voltage, or had a slight slope, and within which the Geiger counter normally would be operated for counting purposes. This experiment, however, was concerned with the high-voltage end of the graph where the counting rate increased sharply with small increases in voltage.

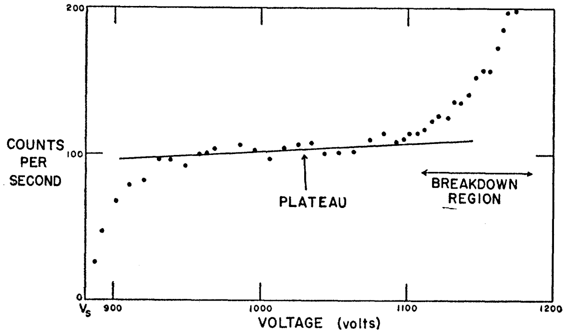

FIG. 4. Total counting rate *vs* voltage.

A straight line drawn through the plateau region gave the average counting rate. The rate of spurious counts was then defined as the difference between the total counting rate and the counting rate on the plateau.

(b) Charge per Pulse *versus* Voltage

A plot of the average number of ions per pulse *versus* voltage, shown in Fig. 5, was composed of two straight-line sections plus a portion which deviated from a straight line at the high-voltage end. Section I rose from zero ions per pulse at V_s to a point designated on the voltage scale as V_B. Section II then continued the straight-line rise from V_B, but with half the slope of Sec. I. This behavior was expected, having been explained by Wilkinson.[7] V_s is defined as the starting voltage, and may also be determined by passing a straight line through the proportional region in Fig. 4, the intercept on the voltage axis for zero counting rate giving V_s. V_B is the voltage at which the charge developed per pulse is equal to the charge across the counter necessary to bring the counter up to the applied voltage.

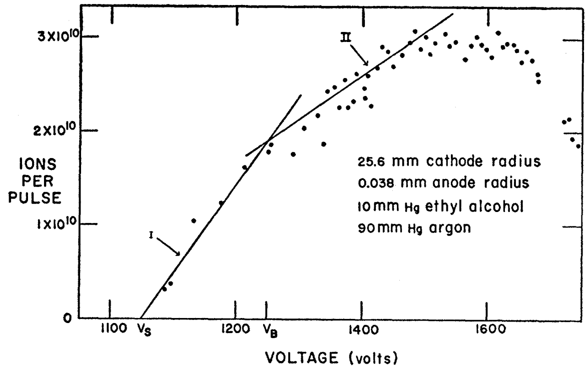

FIG. 5. Average number of ions per pulse *vs* voltage.

A deviation from the straight line of Sec. II was seen at the high-voltage end of Fig. 5, the experimentally determined points dropping toward values of lower ions per pulse. This implied that in this region although secondary pulses contributed to the total counting rate, some were too small to add appreciably to the total charge collected, thereby decreasing the average number of ions per pulse.

IV. DISCUSSION OF RESULTS

(a) Poisitive-Ion Bombardment

To determine whether the rate of spurious counts was related to the plateau counting rate, their ratio was plotted *versus* voltage (Fig. 6). Of course this ratio was zero on the plateau because, within the standard deviation, no spurious counts were detectable in this region. The graph was a straight line over a voltage range depending on the Geiger counter parameters, with a slope that varied from counter to counter. At the high-voltage end of the graph, the straight line changed rapidly into an exponentially rising curve.

The theory of positive-ion bombardment as a source of spurious counts in Geiger counters, as presented by Korff and Present, depended on the probability of a positive ion liberating a secondary electron at the cathode.[1] The ratio, secondary counts per positive ion,

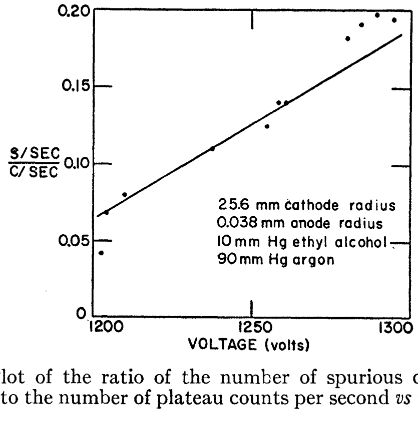

FIG. 6. Plot of the ratio of the number of spurious counts per second to the number of plateau counts per second *vs* voltage.

---

[7] D. H. Wilkinson, *Ionization Chambers and Counters* (Cambridge University Press, Cambridge, 1950), p. 182.

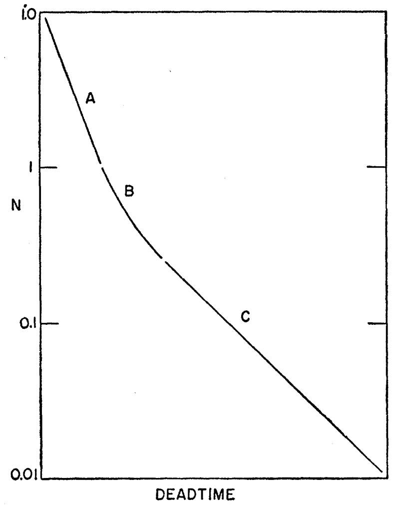

FIG. 7. Log*N* *vs* deadtime, a composite graph.

was obtained by dividing the slope of Fig. 6 by the slope of Sec. II, Fig. 5, because the ratio secondary counts per plateau count was linear with voltage over the region considered, and ions per count was also linear with voltage over the same region. This ratio, secondary counts per positive ion, gave values in the range 1.8×10^{-11} to 5×10^{-11} secondary counts per ion, averaging 2.5×10^{-11} secondary counts per ion for all pressures and electrode diameters used, for argon and ethyl alcohol (since the ions bombarding the cathode are believed to be alcohol ions), and for brass cathodes. This agrees fairly well with the value 3.3×10^{-11} reported by Beretta and Rostagni for the same gases on brass cathodes.[8] It also agrees to order of magnitude with the value given by Korff and Present.[1]

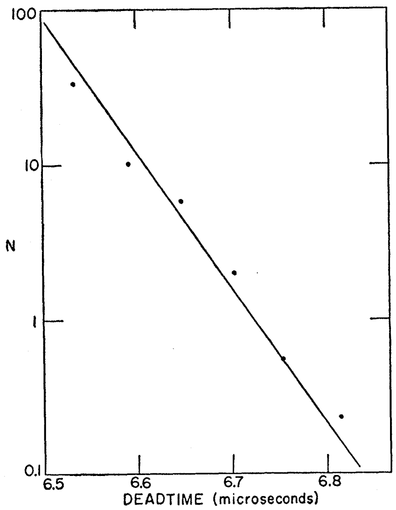

FIG. 8. Log*N* *vs* deadtime for a total pressure of 40 mm Hg.

The deviation, in Fig. 5, of the experimental points from the theoretically expected straight line at the high-voltage end of the plot was correlated with the onset of secondary counts at the beginning of the breakdown region in Fig. 4. The deviation in Fig. 5 did not occur exactly at the voltage at which secondary counts were first noticed in Fig. 4, but at a higher voltage. This voltage difference can be interpreted in the light of the fact that the graph of Fig. 6 was linear over a voltage region corresponding to the beginning of the breakdown region, implying, therefore, that the secondary pulses observed in this region are full-size pulses. Because of the continuation of straight line II over this voltage region, the pulses must have originated near or at the cathode since, only in this way, is a secondary electron capable of traversing the full electric field between the electrodes, giving rise to the full possible amplification on its flight to the anode and therefore to a full-size pulse. Thus, the term "secondary counts per plateau count" is more meaningful when expressed as secondary electrons emitted from the cathode per bombarding positive ion.

(b) Metastable Decay

Other results of this experiment indicate, however, that positive-ion bombardment was not the *dominant* responsible process, for it could not explain the rapid exponential rise in counting rate or in spurious counts per plateau count at the high-voltage end of the graphs. Some other cause must have been responsible for the remaining secondary counts. That these secondary counts were not of full size was illustrated in Fig. 5, where the number of ions per pulse decreased sharply at high voltages though the counting rate and total charge collected per second continued to increase. Although many secondary pulses were added to the total counting rate, they were too small to add appreciably to the charge collected, thereby decreasing the average number of ions per pulse. Furthermore, the rapid deviation from the straight line at high voltages in Fig. 6 implied that there were secondary counts originating in a region other than that near the cathode. Finally, a view of the pulses on a cathode-ray oscilloscope showed pulses in the breakdown region of various heights. Pulses of about 0.1 volt were seen, as small as could be detected by the counting apparatus. The height of pulses on the plateau was in the neighborhood of 7–10 volts.

These clues suggested that pulses were formed between the deadtime and recovery time of the Geiger counter, the smallest pulses having been formed immediately after the deadtime period, and the full-size secondaries from the cathode having been initiated after the recovery time. The small pulses formed close to the end of the deadtime period must have originated somewhere in the gas near the wire because the positive-ion sheath was still traveling across the counter at this time. Therefore, the possible role of metastable atom

---

[8] E. Beretta and A. Rostagni, Nuovo cimento **6**, 391 (1949).

and/or molecule decay through collision with other gas particles was investigated as a cause of these spurious counts.

Let us define N as the ratio of spurious counts (nonfull-size) to full-size pulses. The nonfull-size spurious counts will be shown to arise from metastable atom and molecule decay. The full-size pulses include both primary pulses and spurious pulses initiated by positive-ion bombardment of the cathode. Figure 7 is a composite plot of log$N$ *versus* the deadtime of the counter. The deadtime varied roughly as the reciprocal of the voltage, and it was calculated by using the formula given by Wilkinson whereby the deadtime is a function of the applied voltage V, V_s, V_B, anode radius, cathode radius, total pressure of the gases, and ion mobility[9]:

$$t_d=\frac{b^2\ln(b/a)\exp\left[\dfrac{-2(V-V_s)}{mV}\log b/a\right]}{2K(P/P_0)V[1+\frac{1}{2}m]}, \qquad (1)$$

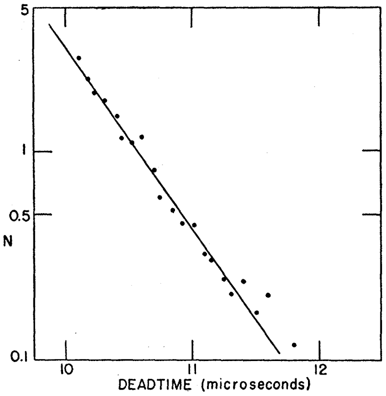

FIG. 9. Log$N$ *vs* deadtime for a total pressure of 200 mm Hg.

where m is equal to the ratio of the charge generated by the discharge per unit length of the wire to the charge per unit length of the counter required to charge it to its operating potential V.

Figure 7 is composed, on the whole, of two straight-line sections, A and C, connected by transition curve B. The slope of Sec. A is approximately four times the slope of Sec. C for argon-ethyl alcohol mixtures, whenever both are present in one graph. For low total pressures of 40 mm Hg (argon plus 10 percent alcohol), only the straight line A is present (Fig. 8). For high total pressures of 200 mm Hg, line C is the highly dominant portion (Fig. 9). At intervening pressures, 60 and 100 mm Hg, the transition curve B dominates the plot with traces of one or both straight-line portions, depending on counter parameters (Figs. 10 and 11).

The resultant theory, developed in this section, makes use of Meyerott's hypothesis that the proportion of metastable molecules to metastable atoms increases with the square of the pressure.[10] Inasmuch as metastable molecules are formed from metastable atom collisions, straight line A, dominant at low pressures, may be considered to represent collisions and subsequent secondary counts initiated by metastable atom decay; and straight line C, dominant at high pressures, may be considered to represent metastable molecule collision and decay. The term N, previously defined, is, of course, not the number of metastables decaying, but it does indicate that metastables existed and subsequently decayed after the deadtime of the initial primary pulse. The following theory shows the dependence of N on time, where time is measured from the initiation of the primary pulse as time zero which, within an infinitesimal time difference, is also the time of the formation of the large number of metastable atoms formed in the initial primary pulse.

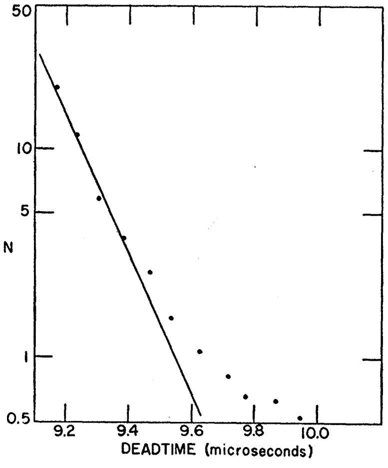

FIG. 10. Log$N$ *vs* deadtime for a total pressure of 60 mm Hg.

Assume that M_0 metastable atoms were formed at time zero. Kruithof reported the ratio of metastable

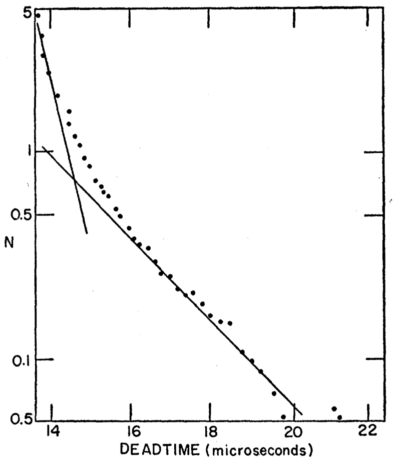

FIG. 11. Log$N$ *vs* deadtime for a total pressure of 100 mm Hg.

---

[9] D. H. Wilkinson, see reference 7, p. 206.

[10] R. Meyerott, Phys. Rev. **70**. 671 (1946).

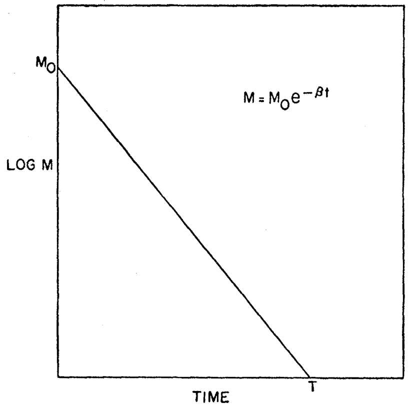

FIG. 12. Metastable atom decay curve.

atoms to ions as approximately 1:1 for argon in the E/p range employed in this research.[11] Because only the number of positive ions could be measured experimentally, this was the only available method of estimating M_0. At any subsequent time t, the number of metastable atoms existing, M, is given by

$$M=M_0e^{-\beta t}, \tag{2}$$

where β is the decay constant, the reciprocal of the mean life of the metastable atoms. This equation is shown plotted in Fig. 12.

The intercept on the time axis is the time T, statistically speaking, when the last metastable exists. When the deadtime of the primary pulse is larger than T, it can be expected, on the average, that no spurious pulse will be initiated. If the deadtime is decreased by increasing the applied voltage, until it coincides with T, then, on the average, one metastable exists that will initiate a spurious pulse, i.e., at this value of the deadtime, $N=1$. If the deadtime is decreased further, becoming less than T, then many metastables exist that may initiate spurious pulses. Only the metastables existing after the deadtime may initiate spurious pulses. However, not all metastables existing after the deadtime may do so, because some may decay during the deadtime of subsequent spurious pulses. M_0, the number of metastables per pulse, also shows an increase, although a slow one, with increasing voltage (Fig. 5). Figure 12 involves $\log M_0$, however; therefore, the increase in $\log M_0$ and in T, with increasing voltage, is very slow and not too important to this theory.

For metastable atoms, at the pressures used in this work, β is given in the form[12,13]

$$\beta=Ap+Bp^2+Cp_i, \tag{3}$$

where Ap represents decay through two-body collision with neutral vehicle gas atoms, Bp^2 represents decay through three-body collision with two neutral vehicle gas atoms, resulting in the formation of metastable molecules, and Cp_i represents decay through two-body collision with quenching gas molecules. The terms in Eq. (3) giving rise to spurious pulses through loss of excess energy by the metastable atom, probably by photon emission, are Ap and Cp_i. The quenching gas molecules, excited by collisions with metastable atoms, have a strong tendency to dissociate rather than reradiate, the fraction of excited molecules reradiating being only about 1 in 10^6. The rate of spurious counts per full-size pulse initiated by metastable atom decay is given, therefore, as

$$\frac{dN'}{dt}=10^{-5}(Ap+10^{-6}Cp_i)M_0e^{-\beta t}, \tag{4}$$

where $N=N'+N''$, N' is the portion of N initiated by metastable atom decay, N'' is the portion of N initiated by metastable molecule decay, and the coefficient 10^{-5} is the efficiency for electron emission by a photon striking the cathode. Integration of this equation gives N' after a time t as

$$N'=10^{-5}(Ap+10^{-6}Cp_i)M_0e^{-\beta t}/\beta. \tag{5}$$

For argon metastable atoms, Phelps and Molnar gave values of $A=40/\text{mm-sec}$ and $B=9/\text{mm}^2\text{-sec}$.[12] These results for pure argon have recently been substantiated in this laboratory by A. Futch and F. A. Grant.

Using Eq. (3) for β in Eq. (5), and setting $M_0=10^{10}$, $N=1$, and $t=\text{deadtime}=9.1$ microseconds (t obtained from Fig. 10 at the point on the curve where $N=1$), the value 1×10^5/mm-sec for C was obtained. This result shows the dominance of the Cp_i term in Eq. (3) although, at 200 mm Hg pressure, Bp^2 may attain values of about 10 percent of Cp_i. It also indicates that Ap is dominant over 10^{-6} Cp_i in Eq. (4) even for 20 percent quenching vapor, the largest used.

Equation (4) can now be rewritten as

$$N'=\frac{10^{-5}ApM_0}{Cp_i}\exp[-(Bp^2+Cp_i)t]. \tag{6}$$

The term Bp^2 was retained in the exponent because it may have a value as much as 10 percent of Cp_i—of possible significance in an exponent.

The formation of metastable molecules in the decay of metastable atoms is expressed by the Bp^2 term. The dominant decay of the metastable molecules is believed to be both by spontaneous decay and by collision with quenching gas molecules. Colli and Facchini reported a spontaneous-decay mean life of 3 microseconds for pure argon.[3] Therefore the rate of change of the number of metastable molecules with time can be expressed as

$$dM''/dt=Bp^2M-(k+Dp_i)M'', \tag{7}$$

where M'' is the number of metastable molecules existing at any time t, k is the reciprocal of the spontaneous-

---

[11] A. A. Kruithof, Physics 7, 519 (1950).

[12] A. V. Phelps and J. P. Molnar, Phys. Rev. 89, 1202 (1953).

[13] M. A. Biondi, Phys. Rev. 82, 453 (1951).

decay mean life, and D is a coefficient representing the number of collisions with quenching molecules leading to decay. Substituting for M from Eq. (2) and integrating, gives

$$M''=\frac{Bp^2M_0}{Cp_i-(k+Dp_i)}\{\exp[-(k+Dp_i)t] -\exp[-(Bp^2+Cp_i)t]\}. \quad (8)$$

Here again Bp^2 in conjunction with Cp_i is retained only in the exponent.

N'' is the ratio of spurious pulses to full-size primary pulses where the spurious pulses are initiated by metastable molecule decay after a time t. The decay term in Eq. (7) is $(k+Dp_i)M''$; therefore, with the fraction of quenching molecules reradiating equal to 1 in 10^6, and with the photon efficiency equal to 10^{-5},

$$dN''/dt=10^{-5}(k+10^{-6}Dp_i)M''. \quad (9)$$

Inserting Eq. (8) for M'', neglecting the term $10^{-6}\,Dp_i$ in comparison with k, and integrating, we find

$$N''=\frac{10^{-5}kBp^2M_0}{Cp_i-(k+Dp_i)}\left[\frac{\exp[-(k+Dp_i)t]}{k+Dp_i} -\frac{\exp[-(Bp^2+Cp_i)]}{Cp_i}\right]. \quad (10)$$

TABLE I. Summary of results, argon-ethyl alcohol, 7.14 mm cathode radius.

Total pressure (mm Hg) p	Quenching gas pressure (mm Hg) p_i	Deadtime (microseconds) t (for $N=1$)	N'	N''
20	2	3	100	
40	4	6.7	15	
		6.7	15	
		6.8	15	
60	6	8.5	2	25
		9.1	1	20
		9.3	1	20
100	5	20	0.1	10
		27	0.2	0.3
100	10	11	0.01	15
		14	0.001	3
100	20	8		3
200	5	19		15
		24		3
200	10	13		15
		14		10
200	20	10		3
		11		2
		15		0.5

TABLE II. Summary of results, argon-ethyl alcohol, 25.6 mm cathode radius.

Total pressure (mm Hg) p	Quenching gas pressure (mm Hg) p_i	Deadtime (microseconds) t (for $N=1$)	N''
100	5	22	2
		24	1
		25	0.5
100	10	14	0.3
		15	0.1
200	5	21	1
		25	1

The graphs of Fig. 7 that contained some portions of both Secs. A and C, for many combinations of gas pressures, gave a ratio of the slope of A to the slope of C of about 4:1 for argon-ethyl alcohol mixtures. Since Fig. 7 was a semilogarithmic plot, this ratio of the slopes was interpreted as being the ratio of the coefficients (Bp^2+Cp_i) to $(k+Dp_i)$ in the exponents of the equations. This signifies that the mean life of metastable molecules is approximately 4 times the mean life of metastable atoms with ethyl alcohol as the quenching agent in the range of gas pressures used. Therefore the term

$$\exp[-(k+Dp_i)t]/(k+Dp_i)$$

is dominant over

$$\exp[-(Bp^2+Cp_i)t]/Cp_i$$

for the pressures and deadtimes involved in the experiments. Therefore,

$$N''=\frac{10^{-5}kBp^2M_0}{Cp_i-(k+Dp_i)}\left[\frac{\exp[-(k+Dp_i)t]}{k+Dp_i}\right]. \quad (11)$$

Solving Eq. (11), setting $M_0=10^{10}$, $N''=1$, and $t=$ deadtime $=25$ microseconds (t obtained from Fig. 7, for 5 mm Hg alcohol and 200 mm total pressure, at the point on the curve where $N=1$), the value 2×10^4/mm-sec for D was obtained. This means that ethyl alcohol as a quenching agent is approximately 5 times as effective on argon metastable atoms as on argon metastable molecules, since $C=5D$. Furthermore, $k=3\times10^5$ indicates that spontaneous metastable molecule decay is of the same order of magnitude as Dp_i, the decay through collisions with the quenching vapor molecules.

Experimental results using Eqs. (5) and (11) are tabulated in Table I for counters with 7.14 mm cathode radius and in Table II for counters with 25.6 mm cathode radius, for argon and ethyl alcohol mixtures. At the dead time, the expected value for N is unity, since when $T=t_d$ (Fig. 12) only one spurious count is expected to be initiated by metastable decay. That most of the results are of the same order of magnitude as unity, is considered good agreement because factors such as the efficiency of a photon liberating a secondary electron at the cathode, and the proportion of ethyl alcohol excited molecules reradiating are known only to an order of magnitude.

(c) Argon-Ethyl Acetate

Argon-ethyl acetate results at 40 mm Hg and 200 mm Hg total pressures, with 10 percent quenching vapor, show longer plateaus that those for the argon-ethyl alcohol mixtures. For example, at 40 mm Hg, the ethyl alcohol plateau is only about 5 volts wide, whereas the acetate plateau is about 40 volts wide. The value of C, determined for ethyl acetate from the preceding equations, was about 1.1×10^5, or approximately the same as C for ethyl alcohol, where C was 1×10^5. To explain the difference in plateau widths obtained between ethyl alcohol and ethyl acetate, a difference of only 10 percent in the value of C is required. However, this is within the experimental error, and, therefore, further conclusions cannot be made. The value of D was the same for ethyl acetate as for ethyl alcohol, within the experimental error.

ACKNOWLEDGMENTS

The authors wish to thank Professor F. A. Grant for much valuable information concerning metastable atoms and Professor R. D. Myers for his many helpful discussions during the course of this work.

PHYSICAL REVIEW VOLUME 98, NUMBER 2 APRIL 15, 1955

High-Frequency Gas Discharge Plasma in Hydrogen*

DAVID J. ROSE, *Bell Telephone Laboratories, Murray Hill, New Jersey*

AND

SANBORN C. BROWN, *Department of Physics and Research Laboratory of Electronics,*
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received January 13, 1955)

The high-frequency electric field required to maintain a hydrogen plasma has been measured as a function of pressure and plasma electron density. A theory of the plasma based on a solution of the Boltzmann transport equation has been developed to predict this field; it agrees satisfactorily with experiment. The theory has no adjustable parameters, and uses only the probabilities of collision, excitation, and ionization of the gas by electrons, and the ionic mobility.

I. INTRODUCTION

MACDONALD and Brown[1] developed a theory of the mechanism of breakdown in hydrogen at high frequencies that is based on a solution of the Boltzmann transport equation. Calculated breakdown fields agree well with their experimental results. More recently, Allis and Brown[2] (A-B) simplified the method of solution and calculation of the high-pressure case, in which electrons diffusing from the discharge do not remove an appreciable fraction of the total energy. This simplified method may also be applied to the calculation of breakdown in certain other gases. The present paper generalizes these theories by taking into account the effect of space charge, so that it will be possible to compute from first principles the microwave field strength required to maintain certain simple plasmas in the steady state. Calculations made on this basis will be compared with experimental measurements obtained for hydrogen.

The theory presupposes that the following additional nonlinear phenomena peculiar to some plasmas and not to breakdown may be neglected: (a) cumulative ionization, (b) electron-ion recombination, (c) formation of negative ions in appreciable numbers, (d) electron-electron interactions, (e) plasma resonance. These restrictions place an upper limit on the plasma electron density for which the theory is applicable. Limits arising from (a), (b), and (c) may be readily calculated. Regarding limit (d), the work of Haseltine[3] shows that the electron-electron interaction has least effect in gases in which the collision frequency of electrons is independent of electron energy. *A posteriori* calculations show that for hydrogen limit (e) actually controls in our experiments, at frequencies of about 3000 Mc/sec, above a density limit of about $10^{11}/\text{cm}^3$, a value well above those experimentally obtained here.

The physical process is the following: Electrons gain energy from the applied field, and lose energy by elastic and inelastic collisions. Ionization of gas molecules provides a source of new electrons, and flow to the tube walls in the presence of density and space-charge potential gradients provides the sink. The Boltzmann transport equation in phase space expresses these balances both in energy and in number; correspond-

---

* This work was supported in part by the Signal Corps; the Office of Scientific Research, Air Research and Development Command; and the Office of Naval Research.

[1] A. D. MacDonald and S. C. Brown, Phys. Rev. 76, 1634 (1949).

[2] W. P. Allis and S. C. Brown, Phys. Rev. 87, 419 (1952).

[3] W. R. Haseltine, J. Math. Phys. 18, 174 (1939).