ing the scattering from (4) and (5) which leads to the expression

$$\cos\beta = \pm\tfrac{1}{3}\sqrt{3}. \qquad (6)$$

We thus see that there are two orientations of the spins which give the same scattering as random orientations. These values of β are of special interest because they are just the angles necessary to give the spin magnetic quantum numbers $+\frac{1}{2}$ and $-\frac{1}{2}$ that are demanded by the theory of spectra. It is of further interest to note that they are arrived at here by classical electrodynamics in an attempt to reconcile experimental results.

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The Discharge Mechanism of Fast G-M Counters from the Deadtime Experiment

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The deadtime of a self-quenching counter is an insensitive time, of the order of 10^{-4} second, which occurs between the time when a counter registers a count and the time at which it has recovered sufficiently to register another count. A simple method of measurement of this time is shown. From a theory developed to explain this deadtime phenomenon it is possible to compute times associated with the deadtime. The check between theory and experiment is very good. The theory involves the formation of a positive ion space charge sheath about the wire of the counter, this sheath expanding to the cylinder. Not only is it possible to show the internal action of a counter by the deadtime experiment, but also it is possible to study the lengthwise spread of that discharge. It was found that the discharge spread throughout the length of the counter, but the spread could be stopped by a small glass bead on the wire. This discovery led to the construction of a directional Geiger counter.

I. INTRODUCTION

A. Historical

SINCE the publication of the original works on G-M counters in 1928 and 1929 by Geiger and Müller,[1] there have been numerous articles concerned with construction techniques, operating properties and theories of discharge of G-M counters. In 1936 the value of the G-M counter as a laboratory instrument was greatly increased by the design of the Neher-Harper[2] extinguishing circuit. Around 1935 and 1936, independently in several laboratories, the fast, or self-quenching, G-M counter was discovered and used. In construction, the fast counters differed from the usual G-M counter only in the addition of alcohol vapor or some other organic vapor to the gas. Many of the operating properties of fast counters were investigated by Trost.[3] The properties of the fast counters differed from those of the usual type G-M counter, here termed a slow counter. In 1940, based primarily on experimental measurements by Ramsey,[4] Montgomery and Montgomery[5] formulated a consistent theory of G-M counter action.

In this present investigation of fast counter action, the most illustrative experiment is that showing the deadtime phenomenon. The deadtime technique herein developed can be used to study the lengthwise spread of the discharge within the G-M counter tube.

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[1] H. Geiger and W. Müller, Physik. Zeits. **29**, 839 (1928); *ibid.* **30**, 489 (1929).

[2] H. V. Neher and W. W. Harper, Phys. Rev. **49**, 940 (1936).

[3] A. Trost, Zeits. f. tech. Physik **16**, 407 (1935); Physik. Zeits. **36**, 801 (1935); Zeits. f. Physik **105**, 399 (1937).

[4] W. E. Ramsey, Phys. Rev. **57**, 1022 (1940).

[5] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **57**, 1030 (1940).

B. Experimental Properties of Fast Counters

In the analysis by Montgomery and Montgomery,[5] the action of G-M counter discharge is pictured as the rapid formation of a positive space charge sheath about the counter wire, followed by the removal of this sheath of positive ions to the cylinder. They then point out that the difference between the action of counters with organic vapor and the action of those without is that, in the organic vapor counters, there are no secondary electrons produced during, or after, the arrival of positive ions to the cylinder, whereas, with the non-organic vapor counters, there are formed secondary electrons which continue the discharge unless the voltage is dropped below threshold, when the positive ions arrive at the cylinder. Although this is not the only difference, as will be shown later, it is still sufficient to necessitate the use of different circuit constants with these two type counters. The action of the organic vapor counter circuit is faster than that of the other type; hence, the names fast and slow counters.

In discussing the experimental properties of a G-M counter, or in comparing different types of counters, it is best to refer to the properties exhibited by the counter when operated in the fundamental G-M counter circuit, shown in Fig. 1, lest the action of a more complicated circuit mask, or change, the properties of the counter. The fundamental circuit consists of the counter, a voltage source and a resistance R in series. There is included a capacity C across the resistance R; this capacity represents the sum of the capacity-to-ground of the counter wire and leads, plus the capacity-to-ground of

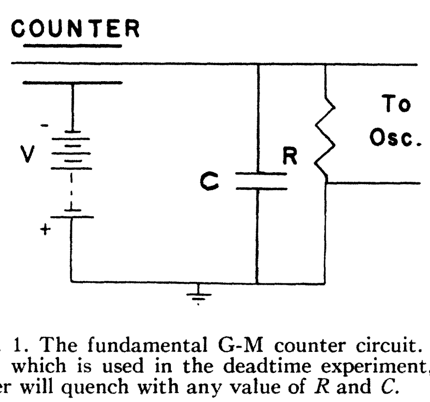


FIG. 1. The fundamental G-M counter circuit. In this circuit which is used in the deadtime experiment, a fast counter will quench with any value of R and C.

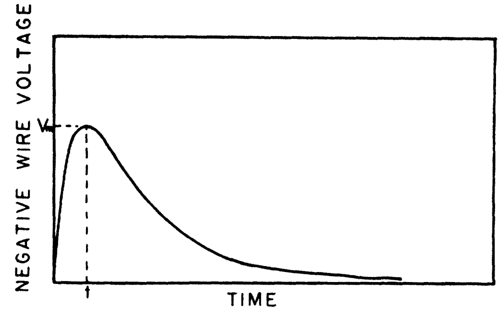


FIG. 2. A typical voltage pulse from a fast counter. As viewed on an oscilloscope with a linear sweep, the voltage across R during a pulse is shown here.

the input of the oscilloscope, or recording circuit, which is being used.

The results of experiments performed in the earlier portion of this investigation enhance previous experimental evidence for certain properties of counters. The results are summarized:

1. Fast counters quench in the fundamental circuit independently of the magnitude of the series resistance R. A fast counter was operated with several values of resistance from 10^9 ohms down to 10^2 ohms. Even with zero series resistance, the fast counter did not go into continuous discharge.

2. The amount of charge which flows in a single pulse in a given fast counter is practically independent of the circuit constants, other than voltage.

3. The voltage across the fast counter does not drop necessarily to the threshold voltage in a pulse. The voltage change may vary anywhere from zero voltage to a value considerably more than the overvoltage which is defined as the voltage above threshold at which the counter is operated. Since the charge is independent of circuit constants, the voltage change in a single discharge should vary inversely as the value of C. This was found to be true if both R and C were varied to keep the product RC constant.

4. The *sine qua non* of fast counter action is the organic vapor present in the gas. Of course, treatment of cylinder walls, choice of material, etc. determines the quality of the counter but, regardless of other treatment, if a counter has organic vapor in it and if it functions at all, it functions as a fast counter.

II. THE DISCHARGE MECHANISM FROM THE DEADTIME THEORY

A. The Deadtime Phenomenon

The phenomenon of the deadtime of a fast G-M counter was found in the course of experiments to measure directly the voltage-time characteristics of a single fast counter pulse. Figure 2 is a drawing of a typical fast counter pulse as estimated from random pulses viewed on an oscilloscope screen. The counter is operated in the fundamental circuit. The breakdown time t_b is extremely short, of the order of 10^{-5} second. Since the writing speeds on an oscilloscope screen, which were necessary for a reasonable size pulse, were greater than those which can be photographed, it was not possible to photograph the single pulses. However, this difficulty was surmounted by using the fact that the pulses from a fast counter are identical in size and shape. An electronic circuit was devised so that many pulses could be superimposed on an oscilloscope screen, thus making the pattern intense enough to photograph. A discussion of the circuit and the experimental procedure will be discussed later.

In the deadtime experiment, the fundamental circuit is used. The vertical plates of an oscilloscope are connected across the resistance R so that the voltage change on the wire during a pulse is delivered to the vertical plates. A small portion of the first part of a voltage pulse is used to trigger off the electronic circuit which then delivers a linear sweep voltage to the horizontal deflecting plates of the scope. The beam is normally at rest at the side of the screen. When an ionizing particle triggers off the counter, the beam traces over the voltage *versus* time curve. This, of course, presupposes that the sweep starts rapidly enough so that the vertical deflection is not very great before the sweep starts. After tracing over a pulse the beam returns to its normal position and awaits another triggering pulse. With a high counting rate, due to a suitably placed radioactive source, the pulse will be traced over and over. With the high intensity of the pattern on the screen due to the superposition of many pulses, the shape can be photographed.

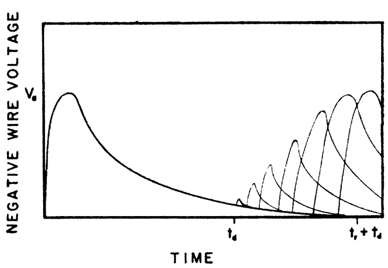


FIG. 3. Drawing of oscilloscope pattern of the result of the deadline experiment. This shows the deadtime t_d and the recovery time t_r. The time (t_d+t_r) corresponds to the arrival of the positive ion sheath at the cylinder. The time t_d corresponds to the point in the transit of the positive ions at which the field about the wire has returned to threshold field.

At a high counting rate there will be numerous pulses from the G-M counter, which arrive after the beam has started to trace over the pattern but before it has returned to its original position. These pulses register on the vertical plates but in no way affect the horizontal sweep. These pulses are expected to occur at random all across the horizontal sweep if the counter is sensitive all the time. *Experimentally, this is not the case.* Figure 3 is a drawing of the actual pattern as viewed on the oscilloscope screen. It is seen that the G-M counter is insensitive for a time t_d, the deadtime of the counter. This deadtime, measured experimentally, is of the order of 10^{-4} second. Moreover, when the counter does regain its sensitivity to ionizing particles, it is not capable of registering a full voltage pulse but regains that ability in the time t_r which is the time from t_d to the appearance of full size pulses. This time t_r is also of the order of 10^{-4} second.

The single traces occurring in increasing size from t_d to (t_r+t_d) cannot be photographed due to their low intensity. However, Fig. 4 is a time exposure taken of the oscilloscope screen, showing clearly the integrated effect of the following pulses as they build up in size from t_d to t_r+t_d. Note that the RC time constant of the fundamental circuit is smaller in the case of the photograph than in the case represented by the drawing; hence the sharp, short pulse in the photograph.

It is wise to examine what this deadtime implies as to the limits of the use of fast counters. It does not imply that fast counters cannot be used in highly resolving coincidence circuits for that use depends on the speed of breakdown. It does however fix the limit on numbers of particles counted per second since the closest together two pulses may occur is of the order of 10^{-4} second. This closest spacing is constant regardless of the shortness of the RC constant.

B. Postulated Mechanism of Fast Counter Action

The deadtime phenomenon is of importance because of the conclusive evidence it presents for a postulated discharge mechanism of fast counters. With the experimental evidence presented above, and former knowledge of fast counter behavior, this postulated mechanism must account for: (1) the very rapid breakdown time of 10^{-5} second or faster; (2) the deadtime, or insensitive time; (3) the building up in pulse size from the deadtime to the recovery time.

Consider a fast G-M counter in the fundamental circuit. When an ionizing particle passes through the counter, in order to be detected, it must form at least one ion pair consisting of a positive ion and an electron, or else knock a photoelectron out from the walls. The electron, or electrons, formed anywhere within the volume of the counter, is accelerated toward the wire. In the region about the wire, cumulative ionization takes place. By some process, as yet unspecified, the discharge spreads along the wire throughout the entire sensitive length of the counter, so that, in the neighborhood of the wire, along its entire length, there is an ion sheath consisting of positive ions, electrons, and probably some negative ions formed by electron capture by neutral atoms. This whole action is assumed to take place in a very short time. Since the ionization took place in the immediate neighborhood of the wire, the electrons and negative ions have but a short distance to be moved by the electric field before they are collected on the wire. This leaves a positive ion space charge sheath around the wire. Of course, this positive space charge would have moved a short distance toward the cylinder while the negatives were being collected on the wire. By this separation of charge the field between the wire and the positive space charge sheath is so reduced that no more ionization can take place. It is interesting and important to note that the charge collected in a single pulse sometime exceeds that necessary for charging the counter to its operating voltage.

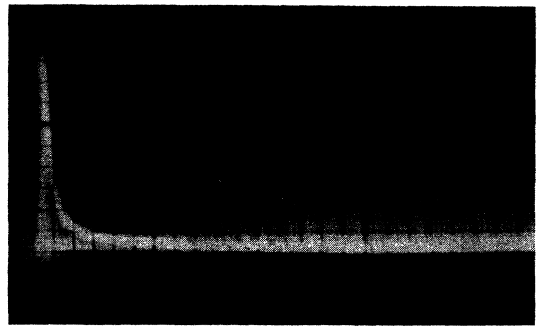


FIG. 4. Time exposure of oscilloscope pattern of the results of the deadtime. This is a one-minute time exposure of the pattern drawn in Fig. 3. Note the envelope of the follow pulses as they build up from t_d to (t_d+t_r).

In this analysis, the fact that the G-M counter is in the fundamental circuit must not be overlooked. Only fast counters are considered here, so the value of the series resistance R may be low. The separation of the positive and negative charges causes the voltage on the wire to drop. This lowering of the wire voltage would continue as the positive ions moved out from the wire region if it were not for the relatively low resistance (10^5). The negative charge collected on the wire leaks off the wire at a rate determined by the RC time constant, so that the voltage V is reapplied across the counter before the positive ion sheath moves very far. The shape of the voltage pulse on the wire is that shown in Fig. 2.

The action of the external circuit is to reapply the working voltage across the counter. This may be accomplished in a very short time, of the order of 10^{-5} second, depending on RC. Even though the voltage is returned to working voltage, the presence of the positive ion space charge sheath lowers the amount of positive charge on the wire, which is necessary for the working voltage to be reapplied. Hence, the field in the region between the wire and the positive ion sheath is so lowered that no more ionization can take place. Even though an ionizing particle passed through the counter, there would be no cumulative ionization about the wire due to the field lowering by the positive ion sheath. This accounts for the internal quenching of a fast counter. It also accounts for the deadtime. As the positive ion space charge sheath moves toward the cylinder, the field about the wire increases since the positive charge on the wire increases in order to keep the voltage across the counter at working voltage. When the space charge sheath has reached a critical distance R, the field about the wire has just returned to threshold counting field, at which time counts may again be recorded. Threshold counting field is defined as that field which exists when the counter is at threshold voltage, with no positive ion space charge sheath present. As the positive ion sheath continues to move to the cylinder, the field builds up from threshold field to the operating field, the latter being reached when the positive ions arrive at the cylinder. Any ionizing particle which goes through the counter would cause a smaller pulse than normal on the oscilloscope if the field were between threshold field and operating field. This is due to the fact that the amount of charge which flows in a single counter pulse depends on the voltage, hence, the field, above threshold at which the counter is being operated.

This picture accounts qualitatively for the observed phenomena. Many observers have postulated the quenching of the ionization by space charge lowering of the field. Some observers[3, 6, 7] have credited an insensitive time to the removal of positive ions. All of their methods were indirect and all of their arguments were qualitative, merely indicating that the order of magnitude of the time was that of positive ion migration. It is to be noticed that the formation and removal of a positive ion sheath postulated above is identical with the mechanism postulated by Montgomery and Montgomery.[5]

C. Deadtime Theory Developed Electrically

The electrical analysis of the mechanism postulated above is to be carried out as a two-dimensional problem, in which end effects are neglected. Figure 5 is a cross-sectional diagram which shows: the wire, of radius a, with a positive charge, Q per unit length; the positive ion space charge, q per unit length at a distance r_0 from the center; and the cylinder of radius b with a negative charge, $-(Q+q)$ per unit length. Assume that there is a potential V across the counter at this time.

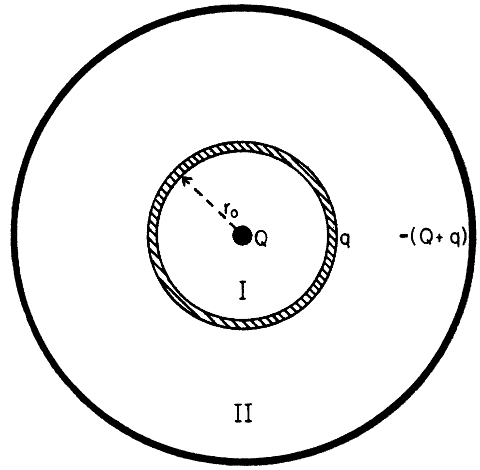


FIG. 5. Cross-sectional view of counter. This shows the positive ion space charge sheath at a point r_0 from the center of the counter.

The field in region I, between the positive ion space charge and the wire, is

$$E_{\mathrm{I}}=2Q/r, \tag{1}$$

where r is the variable distance. In region II the field is

$$E_{\mathrm{II}}=2(Q+q)/r. \tag{2}$$

Since the potential across the counter is V,

$$-V=\int_a^{r_0} E_{\mathrm{I}}dr+\int_{r_0}^{b} E_{\mathrm{II}}dr, \tag{3}$$

and by (1) and (2)

$$-V=\int_a^{r_0} \frac{2Q}{r}dr+\int_{r_0}^{b} \frac{2(Q+q)}{r}dr. \tag{4}$$

Integrating, we have

$$-V=2Q\log(b/a)+2q\log(b/r_0). \tag{5}$$

The charge Q which is necessary for a voltage V, with the other conditions as outlined, is

$$Q=\frac{-1}{2\log(b/a)}\left[V+2q\log\frac{b}{r_0}\right]. \tag{6}$$

[6] H. Aoki, A. Narimatu, and M. Siotani, Proc. Phys. Math. Soc. Jap. **22**, 746 (1940).
[7] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases* (John Wiley and Sons, New York, 1939).

The negative integral of E_I across the counter is now defined as an effective voltage V_e. This effective voltage is the apparent voltage across the counter with reference to counting action, for, when this voltage is above threshold voltage, the field in the sensitive region around the wire is above threshold field so that the counter will count ionizing particles.

$$-V_e=\int_a^b \frac{2Q}{r}$$

$$=\frac{-1}{\log(b/a)}\int_a^b \frac{[V+2q\log(b/r_0)]}{r}dr. \quad (7)$$

Integrating,

$$V_e=V+2q\log(b/r_0). \quad (8)$$

From the postulated mechanism, when V_e equals the threshold voltage V_t, the counter just begins to count, so that then r_0 is the critical distance R. Hence

$$V_t-V=2q\log(b/R). \quad (9)$$

Since both V and V_t are negative voltages, for simplicity, drop the negative sign and consider only the absolute difference. Then

$$R=b\exp[-(V-V_t)/2q]. \quad (10)$$

The critical distance R defining the deadtime is found.

In the experiments to measure deadtime and to check this theory, the wire capacity was relatively high (around 10^{-10} farad), and the resistance relatively low (around 10^5 ohms), so that the voltage pulses were small, and the RC recharging time was short. Then, throughout the entire pulse, V varied very little from V_0. To a very good approximation

$$R=b\exp[-(V_0-V_t)/2q]. \quad (11)$$

The quantity, V_0-V_t, is now termed the overvoltage V_u, or the voltage above threshold at which the counter is operated. Hence, for the experiments to check the theory

$$R=b\exp[-V_u/2q]. \quad (12)$$

D. Ion Mobilities

The experiment described in Section II, A furnishes a method to measure t_d the deadtime and t_r the recovery time, directly. In order to check the theory developed above in Section II, C, an expression for either t_d or t_r in terms of R and other constants of the counter is needed. For this, an understanding of gas ion mobilities is necessary. Loeb[7,8] discusses the subject both from a theoretical and experimental point of view. Due to the great complexity of the field of gas ion mobilities, it is possible, for the purposes of this work, to examine only those factors directly affecting the ion mobilities in a G-M counter.

The mobility constant is the ratio of the velocity of the ion in question to the field strength;

$$k=\frac{dr}{dt}\Big/E, \quad (13)$$

usually expressed in cm/sec./volt/cm. Theoretically, the mobility constant should vary inversely as the number of molecules per unit volume, as measured by the pressure. Loeb[7] states that this law has been verified for pressures from 0.1 mm to 60 atmospheres, so that in the G-M counter work, with pressures ranging from several millimeters to 25 or 30 cm, the law will hold;

$$k=Kp/p_0, \quad (14)$$

where K is the mobility at atmospheric pressure, and p/p_0 is the ratio of the pressure in the G-M counter to normal pressure. The slight temperature dependence of the mobility constant plays no role in the counter experiments for these experiments are carried out at room temperature where most mobility measurements are made.

In self-quenching G-M counters the gas filling is a mixture of, say, a noble gas such as argon and an organic vapor such as alcohol, xylol, or petroleum ether. The simple theoretical expression for the mobility constant of a mixture of gases A and B is

$$k=K_AK_B/(C_AK_B+C_BK_A), \quad (15)$$

where K_A and K_B are the respective mobilities of the pure gases, and the constants C_A and C_B are the partial pressures of the respective

[8] L. B. Loeb, *Kinetic Theory of Gases* (McGraw-Hill, New York, 1927).

components;

$$C_A = P_A/(P_A+P_B), \quad C_B = P_B/(P_A+P_B). \tag{16}$$

Loeb[8] has pointed out that many mixtures do not follow that law and, from his experiments, gives another law,

$$K = K_A K_B/(C_A K_B{}^2 + C_B K_A{}^2)^{\frac{1}{2}}. \tag{17}$$

It is safe to say that, unless data are taken on the mobility of the particular gas mixture used, one cannot be certain of the true mobility. However expressions (15) and (17) are the first approximations.

After a time of the order of 10^{-2} second has elapsed following the formation of the positive ions, their mobilities become smaller probably due to attachment of neutral atoms, resulting in a higher effective mass for the ions. Since the ions migrate to the cylinder in a time less than a tenth of that, the values for newly formed positive ions must be used. These values usually are the same as for negative ions.

In the use of mobility constants, a very critical matter is their dependence on field strengths. At the surface of the wire there is a field higher than 10^4 volts per cm. At the surface of the cathode the fields are considerably reduced, to around 10^2 volts per cm or less, depending on the radius of the cylinder. Loeb[7] and Druyvesteyn and Penning[9] point out that the ratio E/p, usually expressed in volts/cm/mm, is the essential criterion for the energy which ions acquire between collisions. The variation of K with that ratio is important. For a counter with 10-cm pressure, the E/p ratio is around 100 volts/cm/mm at the wire, and at the cylinder it is about 1 volt/cm/mm. Loeb[7] lists, for various gases, the critical ratio below which the mobility constant does not vary with E/p. These critical ratios vary from about 5 volts/cm/mm to about 80 volts/cm/mm. For argon the value is about 5 volts/cm/mm.

Above the critical ratio the mobility constant is no longer constant with a variation of E/p. As E/p is increased, the mobility increases first and then decreases. The functional relationship of this is not known and, moreover, it varies considerably from gas to gas. Hence, an accurate analysis of the deadtime problem is not possible in the region of the wire. However, the recovery time was indicated as that time which the ions needed to migrate from the critical distance to the cylinder. This region is the low field region. The value of the ratio of E/p is below the critical value so that the expression for the recovery time is calculable using the mobility constant as truly a constant.

E. Expression for Recovery Time

The expression for the recovery time is derived rather simply. From (13) the element of time taken for the positive ion sheath to move a distance dr is

$$dt = dr/kE. \tag{18}$$

In this expression E is the field acting on the positive ion sheath. This field is

$$E = E_I + (q/r). \tag{19}$$

The q/r is due to the fact that the force on a surface charge density σ, due to the field of the rest of the surface charge, is $\frac{1}{2}E\sigma$. Hence

$$E = \frac{2Q_0}{r} + \frac{2q}{r}\left[\frac{1}{2} - \frac{\log(b/r_0)}{\log(b/a)}\right], \tag{20}$$

where Q_0 is the charge on the counter when a potential V_0 is across the counter. Note that the second term in the brackets is small compared with $\frac{1}{2}$ for $r_0 = R$, so that it may be neglected. R, experimentally, is from $\frac{1}{3}$ to $\frac{2}{3}$ of the radius of the cylinder. With this analysis it is seen that the positive space charge is moving in a field equivalent to that from $Q_0 + \frac{1}{2}q$ on the wire. Hence, the effective potential across the counter is

$$V = V_0 + q\log(b/a). \tag{21}$$

The field in (1) is

$$E = \frac{V}{\log(b/a)r}, \tag{22}$$

so that (18) becomes

$$dt = \frac{r\log(b/a)dr}{kV}. \tag{23}$$

[9] M. J. Druyvesteyn and F. M. Penning, Rev. Mod. Phys. 12, 87 (1940).

The recovery time t_r is obtained by integrating this from R to b.

$$t_r = \frac{(b^2 - R^2)\log(b/a)}{2kV}. \qquad (24)$$

With the pressure dependence of k substituted in,

$$t_r = \frac{(b^2 - R^2)(p/p_0)\log(b/a)}{2KV}. \qquad (25)$$

If the mobility constant could be correctly assumed constant or if an expression of its variation with field strength were known, the deadtime could also be calculated by integration of (23) from a to R. By assuming the former, we have

$$t_d = \frac{(p/p_0)(R^2 - a^2)\log(b/a)}{2KV}. \qquad (26)$$

This will be shown to give erroneous results.

III. EXPERIMENTAL VERIFICATION OF THE DEADTIME THEORY

A. Measured Quantities

From the postulated mechanism of G-M counter discharge presented in Part II B, there was derived (25), the expression for the recovery time where R is given by (12) and V is given by (21). In order to verify the postulated theory, the recovery time is measured, and compared to the recovery time as calculated from (25). That t_r may be calculated from (25) is seen in an examination of the quantities which appear in the expression. The radii of the wire and cylinder, the pressure, the operating voltage, and the voltage above threshold, are all directly measurable. If the composition of the gas is known, the mobility constant is calculable in a very good first approximation from the expressions given in Part II D. This leaves only the charge per unit length in the positive ion space charge sheath. The total charge which flows in a single pulse is measured quite simply. The voltage source is replaced by a low leakage condenser which is charged to operating voltage. Care is taken to reduce the leakage between the counter wire and cylinder to a minimum. If one then measures a small change in voltage ΔV which takes place in a time t, the total charge which flows in a single pulse is

$$q_t = C\Delta V/st.$$

s is the counting rate of the counter, and C is the capacity of the condenser which is charged to operating voltage. Since it was assumed that the counter breaks down along its whole length, so that the charge in the space charge sheath is uniform along the length of the counter, the charge per unit length in the space charge sheath is found by dividing q_t by the length of the counter.

Experimentally, it was found that q varied approximately linearly with overvoltage, for a given counter and a particular gas mixture. This linear relationship held for different pressures and different threshold voltages, if the same mixture were kept in the counter. From (12), this linear relationship fixes the critical distance R as a constant for a given counter. There is no theoretical significance placed on this linear relationship. In fact, since there was some indication that it broke down for high values of V_u, it is shown that it does not hold in all cases. Nevertheless, when it does hold, it simplifies calculation, and enables one to speak of a particular critical distance, characteristic of a given counter. In the calculation of V for different conditions, each separate value of q must be substituted.

B. Experimental Measurement of the Recovery Time

In Part II A, it was pointed out that the deadtime phenomenon was discovered in the course of experiments to measure the voltage-time characteristics of the G-M counter pulse. A writing speed of about 10^5 inches per second on the oscilloscope screen is needed to get a pattern of the fast breakdown of the G-M counter. From data given in a commercial cathode-ray tube catalog,[10] this is about 10 times as fast as it is possible to photograph in a single trace. For that reason a superimposition of pulses was required. Several methods were tried. Since two of the methods can be used in the deadtime work, they will be discussed.

[10] Catalog B, Allen B. Dumont Laboratories, Inc. Passaic, New Jersey.

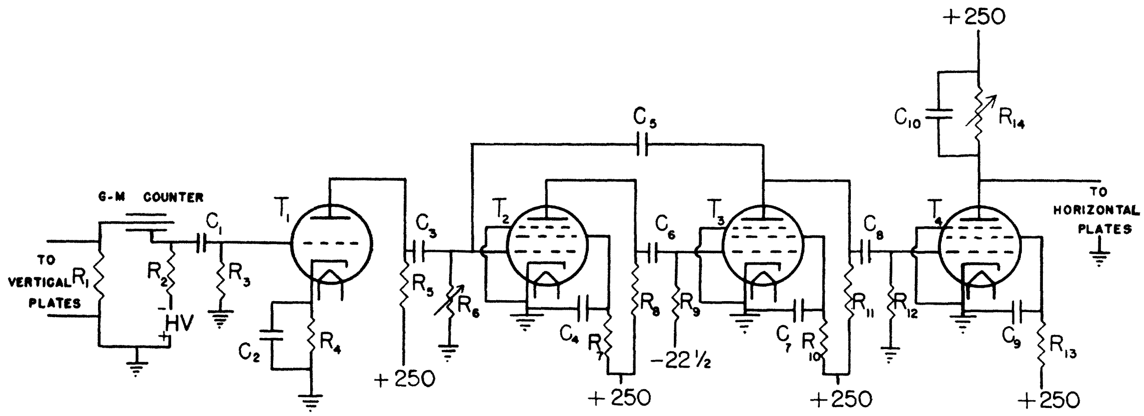
In most oscilloscopes the linear sweep on the horizontal is furnished by the sawtooth voltage pulses from a gas discharge, relaxation oscillator, which employs a Type 885 gas triode tube. Single sweeps are obtained by biasing the gas tube sufficiently high that the ratio of plate voltage to negative grid voltage does not exceed the firing ratio which is in general about 10. To trigger the single sweep, a positive pulse is fed onto the grid. When fired, the tube discharges a condenser in the plate circuit till the plate voltage drops sufficiently for the grid to take control again. Then the first part of the RC exponential recharging of the condenser is used as the linear sweep. Since the time of firing the gas tube is about 10^{-5} second it is impossible to get the breakdown portion of the G-M counter pulse on the linear sweep. However, it is possible to measure the deadtime and recovery time since they are of the order of 10^{-4} second. For the work here reported, an RCA 155 oscilloscope was made to work as a single sweep instrument by increasing the bias on the 884 relaxation oscillator tube. In practice it was not possible to get away from a non-linear return sweep but the return sweep was calibrated with a sine wave oscillator so the difficulty was surmounted.

A more convenient method of getting the deadtime pattern also originated in attempts to measure the breakdown characteristics. It has several advantages over the method described above. In it, a different circuit is used to obtain the single horizontal sweep. When triggered, the circuit starts the electron beam of the oscilloscope across the screen in a linear sweep at the end of which it returns it rapidly. This is a decided advantage over the relaxation oscillator which first swings the beam across the screen and returns it in an exponential sweep, for, in the latter case, part of the pulse to be measured is over before the sweep starts.

The circuit is diagramed in Fig. 6. A positive pulse is fed onto the grid of T_1 from the cylinder of the G-M tube. T_1 is an isolation stage to prevent feedback from the rest of the circuit to the fundamental circuit. This feedback would distort the characteristics of the negative pulse which is fed onto the vertical plates of the oscilloscope from the wire of the G-M counter. A negative pulse is then passed onto the grid of T_2 which together with T_3, acts as a multivibrator biased to prevent self-oscillation. The circuit characteristics of multivibrators are discussed adequately by Neher[11] or in many electronics textbooks. Briefly, its action is described here. A negative pulse fed onto the grid of T_2 starts to cut off the current, for normally T_2 is conducting. This action passes a positive pulse through the large condenser C_6 to the grid of T_3, which normally is biased to cut off. The negative pulse which T_3 puts out is fed back onto the grid of T_2 through the condenser C_5. This causes T_2 to become even less conducting. The result of this action is that the plate of T_3 drops in voltage very rapidly. When the charge on the grid of T_2 has leaked off, the whole action is reversed. The result is a square pulse output from the plate of T_3. The natural length of this square pulse is determined by the RC discharge rate of the grid of T_2. The resistance R_6 is variable so that the length of the square pulse can be changed. The square pulse output from T_3 is fed onto the grid of T_4 which is normally in a conducting state. The plate is nearly at ground potential, most of the voltage drop being across the resistance R_{14}. The condenser C_{10} is charged to a voltage i_pR_{14}, where i_p is the plate current of T_4 in the conducting state. Since the plate voltage swing of T_3 is nearly the full 250 volts, T_4 is cut off completely. C_{10} begins to discharge through R_{14} and continues until T_4 again becomes conducting. If the natural length of the multivibrator pulse is shorter than the $R_{14}C_{10}$ time constant, the voltage pulse from the plate of T_4 is a nearly perfect sawtooth. This voltage pulse is fed onto the horizontal plates of the oscilloscope. The linear sweep which it causes starts with a time delay of around 10^{-6} second from the time T_1 receives the trigger pulse.

The circuit described above was used in obtaining the picture of the deadtime and the recovery time shown in Fig. 4. With it, measurements of the recovery time and the deadtime may be made. It is not necessary to photograph the pattern on the oscilloscope screen, for visual

[11] H. V. Neher, in *Procedures in Experimental Physics* by John Strong (Prentice-Hall, New York, 1928).



$R_3, R_{12}, R_{14} = 10^6$ OHMS	$R_7, R_{10} = 10^4$ OHMS	$C_1 = .001$ MFD.	$C_6, C_8 = .01$ MFD.	T_1 -- 37
$R_4 = 5 \times 10^3$	$R_8 = 2 \times 10^3$	$C_2 = 10$	$C_9 = .1$	T_2, T_3 -- 6AG7
$R_5, R_{13} = 10^5$	$R_9 = 10^7$	$C_3, C_5 = .0001$	$C_{10} = .0025$	T_4 -- 6SJ7
$R_6 = 2 \times 10^6$	$R_{11} = 1.5 \times 10^4$	$C_4, C_7 = 8$		

FIG. 6. Circuit used in deadtime experiment. It consists of the fast counter in the fundamental circuit; T_1 which is an isolation state; T_2 and T_3, which act together as a multivibrator; T_4, which together with R_{14} and C_{10} give a sawtooth pulse when T_4 is rapidly biased to cut off.

measurements on a ruled screen are sufficiently accurate.

C. Comparison of Calculated and Observed Recovery Times

In Parts III A and III B, a description of the methods of measurement for the various quantities was given. In this section, results of those measurements are to be presented.

In (25) the quantities a, b, R, K and p_0 are constants for a particular counter. One can get a variety of different conditions by varying the pressure in the counter containing a given gas mixture. It is possible to vary the pressure of an argon-xylol, 9 to 1, mixture from about 16 cm to about 1 cm pressure and still have a good fast counter. Argon-xylol counters will work as fast counters at much higher pressures but the percentage of xylol must be lower, since the vapor pressure of xylol at room temperature is around 16 mm.

A permanent glass system with provision for changing cylinders, wire, and gas, was used in these experiments. It was far more convenient than making a new sealed-off counter for every change in the parameters.

The first counter used to test the theory was a copper cylinder counter which had been given the NO_2 treatment. This treatment consists in heating the counter cylinders in the presence of NO_2 gas, after first cleaning them with nitric acid and rinsing. A velvety black or dark brown color of the copper cylinder results. The NO_2 is then pumped out. The first counter was 15.3 cm long by 1.11 cm radius with an 0.010-cm tungsten wire. The gas filling was a 9 to 1, argon-xylol mixture. The critical distance R was calculated to be 0.65 cm. Table I gives the data taken with that counter. The pressure was varied from 13.2 cm to 5.0 cm. The threshold voltage changed from 1410 to 985 volts. The threshold voltage is given in parenthesis for each different pressure. The calculated and observed values of t_r are listed for each different set of conditions. Note the good agreement and that the variation of the observed t_r follows closely that of the calculated t_r.

The value of 0.8 for the mobility constant is the average of the values obtained from the two formulae in Part II D. The two values are 0.6 and 1.0. These are obtained with 1.8 as the mobility constant of newly formed positive argon ions and 0.2 for the mobility of xylol ions. This last value is obtained as an estimate from tables[12] listing mobilities of close relatives of

[12] *International Critical Tables*, National Research Council (McGraw-Hill, New York, 1926).

Table I. Calculated and observed recovery time.

$b=1.11$ cm Pressure (cm)		$a=0.010$ cm Voltage (V_0)	$K=0.8$ t_r (calc.) (sec.)	$R=0.65$ cm t_r (obs.) (sec.)
13.2		1470	2.4×10^{-4}	2.2×10^{-4}
	(1410)	1540	1.6	2.1
		1620	1.6	2.0
		1680	1.5	1.9
11.0		1380	1.9	2.0
	(1290)	1450	1.6	1.9
		1515	1.4	1.8
		1612	1.2	1.7
9.0		1270	1.7	1.7
	(1200)	1330	1.5	1.7
		1375	1.3	1.6
		1500	1.0	1.5
7.0	(1115)	1235	1.3	1.4
		1445	0.8	1.2
5.0		1045	1.1	1.2
	(985)	1140	0.9	1.1
		1215	0.8	1.0

xylol. The value of 0.8 may be in error by 30 percent but, even so, the agreement with all predictions of the theory is very good.

As a check on the above, and as further verification of the theory, a counter of different dimensions was investigated. The radius was 1.43 cm. The gas in this counter was an argon-xylol mixture but this time it was 5 percent xylol and 95 percent argon. Although the radius b was larger, the value of q was so much smaller than in the previous case that R, the critical distance, was only 0.47 cm. With the different gas mixture, the value of K was 1.0, obtained as before. In this particular experiment, a better condenser was used in the measurement of q so that the final data are expected to be more accurate. The results are given in Table II. Even though the conditions are such to give calculated recovery times more than twice those of the other counter, there is still excellent agreement between calculated and observed recovery times.

The data herein presented, along with other data on less complete runs with different counters, seem to give sufficient verification of the theory of counter discharge.

D. Comparison of Calculated and Observed Deadtimes

The deadtime may be measured by the same method as used for the recovery time. As discussed in Part II D, the simple expression for the deadtime derived in Part II E is not accurate. To show the discrepancies between the observed deadtime and the calculated deadtime, Table III tabulates the results for the counter to which Table II refers. The observed deadtime is 4 or 5 times as long as the calculated deadtime. Not only for this counter but also for other counters, this fact was observed. The apparent mobilities are much lower in the high field region. There is still observed a dependence of the deadtime on the pressure/voltage ratio.

Although the deadtime can be used only in a semi-quantitative way to prove the theory, it is still an important quantity to measure. It is the quantity which determines the maximum counting rate of fast counters. In a particular experimental set-up, the size of the voltage pulse necessary to trip the recording circuit must be known. Then the insensitive time of the set-up may be measured experimentally as that time from the beginning of a trigger pulse to the time when the follow pulses have built up to the required size. The experiment employing the RCA 155 oscilloscope takes but a short time to perform. After it is set up, the insensitive times can be measured for a large number of counters very quickly.

IV. DEADTIME TECHNIQUE APPLIED TO DISCHARGE SPREAD

A. The Spread of the Discharge

In the postulated mechanism of discharge of Part II B, it was assumed that the discharge spread throughout the full length of the counter in a time short compared with the 10^{-5} second breakdown time. The excellent agreement with experiment of the predicted action from that theory seems to justify the assumption. In fact,

Table II. Calculated and observed recovery time.

$b=1.43$ cm Pressure (cm)		$a=0.010$ cm Voltage (V_0)	$K=1.0$ t_r (calc.) (sec.)	$R=0.47$ cm t_r (obs.) (sec.)
13.4	(1320)	1370	4.5×10^{-4}	4.3×10^{-4}
		1480	4.5	4.3
11.0	(1185)	1235	4.2	4.3
		1360	4.3	4.2
9.0	(1080)	1145	3.7	3.7
		1230	3.6	3.1
7.0	(985)	1035	3.3	3.6
		1170	3.0	3.1

in view of the identical nature of the pulses in size and shape, it is hardly possible to assume anything but complete, and uniform, spreading of the discharge along the counter length. With the deadtime theory so convincingly supported by experiment, an examination of the spreading of the discharge was undertaken. Many of the experiments herein reported were performed before the complete theory was worked out; they contributed immeasurably to the formulation of the theory.

Some time before the deadtime technique was discovered, Professor Brode of the University of California described to the author an unpublished experiment on the spread of discharge in counters. This experiment, referred to as the Brode experiment, was performed with a double counter, i.e., a single glass tube container with two cylinders and two wires. The cylinders, end to end, were separated by a fraction of an inch. The wires were supported in the middle by an insulating glass bead. The pulse from either counter could be taken from its wire or its cylinder. Brode connected one wire to the vertical plates of an oscilloscope and the other wire to the horizontal. If one counter fired without the other the electron beam of the oscilloscope would undergo a horizontal or a vertical displacement. If both fired coincidentally, either from a true coincidence or from the spread of the discharge from one to the other, there would be a 45° deflection of the beam. This assumes equal pulses from each counter. Brode found that, if both counters were slow counters, the discharge did spread. For fast counters the discharge did not spread; most pulses were either vertical or horizontal, very few 45° deflections being observed.

In repeating the Brode experiment, the author found similar results. There is, of course, the possibility that some of the occasional coincidences observed were from discharge spreading but the number was so small that it did not indicate a uniform spreading of the discharge along the counter. This experiment was interpreted as an indication that the discharge was localized. It definitely eliminated photoelectric action on cathode and in the gas as a mechanism for discharge spread. When the deadtime technique was discovered and supported so well, this whole question of discharge spread was reexamined, for the deadtime theory demands that the discharge spread along the unobstructed wire.

TABLE III. Calculated and observed dead time.

$b=1.43$ cm Pressure (cm)	$a=0.010$ cm Voltage	$K=1$ t_d (obs.) (sec.)	$B=0.47$ cm t_d (calc.) (sec.)
13.4	1370	2.6×10^{-4}	0.65×10^{-4}
	1480	2.5	0.52
11.0	1235	2.4	0.60
	1360	2.3	0.46
9.0	1145	2.1	0.52
	1230	2.1	0.41
7.0	1035	1.8	0.43
	1170	1.7	0.32

B. Divided Cylinder, Divided Wire Counter

In order to see if the deadtime, as well as the discharge, spread in the type counter described in Part IV A, a similar counter was built. This, along with other multiple counters, is diagramed in Fig. 7. The over-all length was about 8 inches, the two cylinders being separated by about $\frac{1}{4}$ inch. The two wires were held together mechanically, but separated electrically, by a glass bead about $\frac{1}{8}$ inch in diameter. All gas fillings in the multiple counters considered in this section were 9 to 1, argon-xylol, mixture. Each counter exhibited the deadtime and, because of equal dimensions, the two deadtimes were the same.

The particular deadtime experiment performed on this and other multiple counters needs some explanation. If two counters, say A and B, are connected in parallel, then a count from either of them may act as a trigger pulse for the linear sweep in the deadtime experiment. Moreover, a count from either of them may act as a follow pulse. If the two counters are independent, as far as deadtime is concerned, there will be no definite deadtime for the combination. This is because, although the one which gave the trigger pulse, say A, is dead for a short period thereafter, the other, B, is still sensitive. The same holds true if B furnishes the trigger pulse, for then A is still sensitive. On the oscilloscope screen this shows as the customary deadtime pattern, as illustrated by Fig. 4, except there are additional pulses filling in the open space from $t=0$ to $t=t_d$.

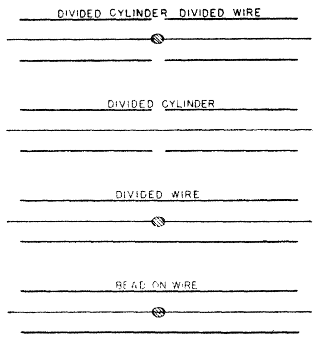


FIG. 7. Diagrams of special counters. These counters are forms used in the study of the lengthwise spreading of the discharge in fast counters.

If the two counters are not independent with respect to deadtime, then the customary deadtime picture with no modification is expected. Also, when the discharge spreads from one counter to the other, the resulting voltage pulse is the sum of the individual voltage pulses.

In order to test the spread of the deadtime in the divided wire, divided cylinder counter, the two separate counters were connected in parallel. The deadtime did not spread. There were, of course, a few double pulses from either true coincidences or occasional discharge spread.

C. Divided Cylinder Counter

The next step was to test to see if the deadtime and discharge would spread in a counter with a divided cylinder but a single wire. Again the counter, diagramed in Fig. 7, was 8 inches overall. When the pulses were taken from the cylinders individually, each of the counters exhibited the same deadtime. When the cylinders were paralleled externally it was found that the deadtime did spread. Moreover, the discharge spread too, for the voltage pulses were the sum of the voltage pulses of the individual counters. The counters acted together as a single counter. In other words, it was not the divided cylinder but the wire divided by the glass bead which prevented the spread of discharge and deadtime in the experiment of Part IV B.

One very interesting and important fact was observed in the performance of Brode's experiment on the divided cylinder counter by taking the pulses from the two cylinders. As expected from the results of the deadtime experiment, all the deflections were at 45°. However, when these deflections were examined closely, it was found that the counter which received the ionizing particle did start slightly ahead of the other. To test this, a radioactive source was moved from one end to the other. This indicated definitely that the spread of discharge does take a measurable, finite time. This time was estimated to be but a fraction of the breakdown time or around 10^{-6} second or less. This spreading of the discharge down the length of the counter in a time, short compared with the breakdown time, was assumed in the postulated theory of discharge. It is comforting to note that it is verified experimentally.

D. Divided Wire Counter

Merely as a check on the experiments of Part IV C a divided wire counter was made as diagramed in Fig. 7. The over-all length of the single cylinder was 8 inches. As was expected, neither the deadtime nor the discharge spread. These experiments were sufficient to indicate that a spread of the discharge implied a spread of the deadtime. All the experiments agree with the theory of the deadtime.

E. Bead on Wire Counter

In the deadtime experiment, performed with the divided wire counter, the two wires were externally connected electrically. Hence, it was concluded that the spread of the discharge was a surface phenomenon on the wire or some phenomenon occurring in the gas very close to the wire. To test that conclusion, a counter was constructed with a single cylinder and single wire but with a glass bead about $\frac{1}{8}$ inch in diameter and $\frac{1}{4}$ inch long on the wire in the center of the counter. This counter is diagramed in Fig. 7.

Although Brode's experiment could not be performed with this counter, there still remained two methods with which the spread of the discharge could be investigated. The experiments on the spread of the deadtime and the size of the voltage pulses were still applicable to the problem. When tested with the deadtime experiment, the counter was found to behave as two. The discharge did not spread. This was corroborated by the pulse size experiment. *A glass bead on the wire was sufficient to prevent the spread of the* *discharge.* In the previous experiments, it was not the fact that either the cylinder or the wire were divided but the fact that there was a glass bead on the wire that prevented the discharge from spreading. No longer does one conclude from Brode's experiment that the discharge is localized. It spreads along the unobstructed wire; but a small glass bead is sufficient to stop it. This experiment shows that a new mechanism must be used to account for the spread of discharge, for, previous to Brode's experiments, it was thought to be photoelectric action on the cylinder and from the time of Brode's experiment to very recently, it was considered to be localized.

F. Small Bead on Wire Counter

The next step in the investigation of the discharge spread was to find the minimum bead size which would stop the spread of discharge. For that purpose an 0.022-inch diameter bead was put on an 0.008-inch diameter wire. Instead of sealing off the counter constructed with this wire, the deadtime experiment was performed at several pressures. At 10-cm pressure with an operating voltage of 1300 volts, the deadtime did not spread; the counter acted as two counters. The same held true at 6.5-cm pressure with an operating voltage of 1100 volts. However, at 3.5-cm pressure the action changed. From the threshold voltage of 790 volts to 840 volts, the deadtime did not spread. As the voltage was increased above 840 volts, more and more double sized counts appeared until all counts were double sized. Then there was a unique deadtime. The counter had changed in action from that of two apparently separate counters to that of a single counter.

A partial explanation of this phenomenon is obtained if a fact mentioned in Part II D is examined. It was there indicated that the quantity which determines the energy which an electron gains between collisions is the ratio E/p. This is obvious since E is a measure of the energy gained per unit path and $1/p$ determines the mean free path. For a particular gas, or gas mixture, there is a critical value of E/p for which the electrons gain sufficient energy between collisions for cumulative ionization to take place. As the voltage across a G-M counter is raised, the threshold voltage is reached when the critical value of E/p is obtained near the wire. As the voltage is raised above threshold, the point at which the critical value of E/p is obtained is pushed out from the wire so that the volume which is sensitive to cumulative ionization is increased. This increase in the sensitive volume probably accounts for the observed increase with overvoltage of charge flowing in a single pulse. Although this ratio of E/p has a critical value, cumulative ionization is not obtained in a limited space, such as the region of the wire, if the pressure is too low, for then there are not enough collisions for very rapid multiplication.

With this in mind the explanation of the change in action of the small beaded counter is clear. As the pressure was lowered, the operating voltage decreased but not as rapidly as the pressure. Since

$$E=\frac{V}{r\ln(b/a)}, \tag{27}$$

the value of E/p at a given radius then increased. At the pressure 3.5 cm, with an operating voltage of 840 volts, the sensitive region had been pushed out from the wire till its radius exceeded that of the bead. Then, the discharge could spread.

G. The Directional Geiger Counter

The results of Parts IV A through IV F point out the experimental basis of the discovery of the directional Geiger counter which was reported[13] earlier. The fact that a small glass bead on the wire would localize the counter discharge by preventing the spread along the wire immediately suggested the idea of separating a single counter into sections which could be used in coincident arrangement.

The behavior of the directional counter well illustrates the efficiency of the bead in preventing the discharge spread. This of course assumes that the counter cylinder has been treated to give a low photoelectric emission and a high work function. It is known that the NO_2 treatment of copper gives such a surface. Unpublished results of some photoelectric experiments show this to

[13] H. G. Stever, Phys. Rev. **59**, 765 (1941).

be true. Also, this work with beads on the wire has been tried only with organic vapor filled counters.

V. CONCLUSIONS

It is in order to examine the implications of the deadtime phenomenon with reference to the use of a G-M counter as a laboratory instrument. It is obvious that the deadtime in no way limits the use of these counters in highly resolving coincidence circuits, for the high resolution in those circuits depends upon the speed of potential fall of the wire, which is known to be fast. However, the deadtime does limit the maximum counting rate at which these counters can be used since there is an absolute minimum time, t_d, between recorded counts. This time is easily measurable and is of the order of 10^{-4} second. Even though the RC recharging time in the fundamental circuit is reduced to a minimum, the deadtime, or insensitive time, is present.

Even though there is a limit to the counting rate, the self-quenching, organic vapor filled counter still justifies the name, fast. It can be used in a circuit which reacts more rapidly than the one used with what has been termed a slow counter. Montgomery and Montgomery[5] point out that the only difference between the organic vapor filled counter and the other type is that, in the organic vapor filled counter, the positive ions do not knock out electrons when they arrive at the cylinder wall, whereas in the usual type counter they do. This implies that with the fast counter one can use a low resistance and take advantage of the maximum counting rate, limited only by the deadtime. With a slow counter the voltage across the counter must have dropped to threshold, or below, when the ions arrive at the cylinder lest the secondary electrons continue the discharge. This necessitates a larger resistance with the slow counter so that the voltage takes considerably longer to return to full operating voltage.

Besides the presentation of a clear, simple picture of the internal action of a fast G-M counter, the deadtime experiment can be applied to the problem of the discharge spread in a fast counter. It is not applicable to discharge spread in slow counters. It is seen from experiments described in Part IV of this paper that the spreading of discharge is quite localized, being confined to the region of the gas about the wire. The small-bead-on-wire counter experiment however indicates that the spreading action takes place in the gas rather than right on the surface of the wire. The lengthwise spread of the discharge may be due to a photoelectric action which is particularly selective to the gas in the region of the wire. This would imply that a function of the organic vapor is to absorb the photons emitted in the cumulative ionization region about the wire. Perhaps, on the other hand, the lengthwise spread of the discharge is due to a scattering phenomenon. This could be tested by some experiments with beads on the wire by reducing the length of the bead but keeping the diameter constant. Eventually a point might be reached where the scattered electrons would jump over the short bead. If it were a photoelectric spread, a quartz bead might allow the passage of the ultraviolet photons which were responsible whereas a glass bead would absorb them.

The author wishes to take this opportunity to thank both Professor H. V. Neher and Dr. W. H. Pickering. Throughout the entire experiment on counters their aid was always available and often sought.

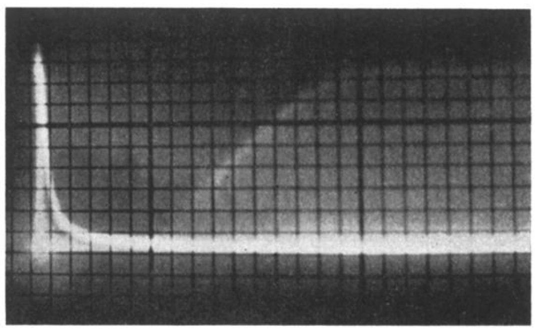


FIG. 4. Time exposure of oscilloscope pattern of the results of the deadtime. This is a one-minute time exposure of the pattern drawn in Fig. 3. Note the envelope of the follow pulses as they build up from t_d to (t_d+t_r).