The Discharge Mechanism of Geiger-Mueller Counters

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The measurements of W. E. Ramsey on the variation with time of the potential across a Geiger-Mueller counter (see preceding paper) are interpreted on the basis of the inductive action of the positive ion space charge moving across the counter. This inductive action, together with the hypothesis that the positive ions may eject electrons when they reach the cathode, furnishes a reasonable explanation of both the fast and slow types of breakdown of counters. This postulated mechanism leads to simple explanations of the quenching of a counter discharge and the necessary conditions for the maintenance of a steady discharge. In particular, it is predicted and verified experimentally that it is possible to operate a counter even when the potential is considerably in excess of that required for a continuous discharge, provided that the capacity of the counter wire is sufficiently reduced. A simple, although indirect, method is described for measuring the breakdown characteristic of a counter which gives results in good agreement with the direct determinations of W. E. Ramsey.

1. INTRODUCTION

THE technique of the preparation and the proper use of Geiger-Mueller counters is beset by many difficulties, not the least of which are the numerous statements of the mechanisms and behavior of counters under particular conditions which are so voluminous and self-contradictory as to cause extreme confusion. Indeed, our understanding of counter behavior is so vague that only recently it was stated that "the use of Geiger counters . . . has been practically abandoned because they have been found to be unreliable." [1] The excellent measurements of the variation with time of the potential across a counter described in the preceding paper by W. E. Ramsey[2] suggest an explanation of the discharge mechanism which allows the clearing up of many inconsistencies in the behavior of counters as recorded in the literature of the subject. We wish to outline this mechanism in some detail below, and endeavor to show which features of counter behavior can be removed from the realms of magic to simpler planes of thought.

2. THE DISCHARGE MECHANISM

Let us suppose for convenience that the cylinder of the counter is at zero potential and the wire at some high positive potential. Then if one or more ion pairs are produced within the counter, the electrons will be accelerated toward the wire. When they reach the high field region in the neighborhood of the wire, they will produce ionization by collision, and the number of electrons will grow to a large value if the wire potential is sufficiently high. It may be that this multiplicative process involves the emission of photons which eject photoelectrons from either the gas or the counter cathode,[3] which also multiply when they have come near the wire. At any rate, the total number of positive ions will increase until their space charge so decreases the field near the wire that ionization by collision by electrons no longer takes place. Since the mobility of electrons is much greater than that of positive ions, we may suppose that all electrons are collected on the wire before the positive ions have moved appreciably. The average distance which the electrons move before collection is extremely small, always less than a wire diameter, and consequently the change in potential produced by this motion is small and may be neglected. The production of new ions has ceased, and the positive ions now move outward from the wire. As they move the potential on the wire changes, but nothing else occurs until the ions reach the cathode surface. Here, if the conditions are suitable, they may eject further electrons[4] which are accelerated to the wire and the whole process

[1] O. S. Duffendack, H. Lifschutz and M. M. Slawsky, Phys. Rev. **52**, 1231 (1937).
[2] W. E. Ramsey, Phys. Rev., this issue.
[3] E. Greiner, Zeits. f. Physik **81**, 543 (1933).
[4] A. von Hippel, Zeits. f. Physik **97**, 455 (1936).

repeats itself if the potential of the wire is sufficiently high at this time. If the potential is too low, the succeeding multiplication will be small and produce only a small additional change of potential. If no electrons are ejected, the discharge is completed in the first stage. We shall show below that this critical potential is close to that ordinarily designated as the starting potential. We now proceed to show how well the mechanism described above furnishes a satisfactory explanation of many observations of the behavior of Geiger counters.

3. The Interpretation of Ramsey's Experiments

W. E. Ramsey has expressed the principal result of his measurements of the time variation of the wire potential by the empirical relation

$$V=V_0-(k/C)\log(t/t_0+1), \tag{1}$$

where V is the potential of the wire at the time t, V_0 the potential at the time $t=0$, C the capacity of the counter wire and the bodies connected to it, and t_0 and k are empirical constants. This expression is valid over a considerable variation of the conditions as is evident from Ramsey's Figs. 4 and 6. For a particular counter, k depends only upon V_0, and t_0 is a constant. According to the picture of the discharge mechanism stated above, the variation of potential expressed by this formula merely represents the potential changes of the wire caused by the inductive action of the positive ions as they cross the counter. It is therefore possible to submit the matter to calculation. Unfortunately, we are handicapped greatly by our almost complete ignorance of the mobility of a positive ion in the extremely high fields which are present in a counter. We expect the mobility not to be a constant, but to depend upon the field strength, and in perhaps quite a complicated manner.[5] It is possible, however, to show that for reasonable forms of the variation of the velocity of the ions with field strength, the wire potential will be given by an expression of the same form as Eq. (1).

Let Q be the charge per unit length on the counter wire, and let us assume that there is a space charge sheath, of negligible thickness and of charge q per unit length, of positive ions at a distance r from the axis of the counter wire, extending for a length l along the counter. The wire potential, V, will be given by

$$V=\int_r^{r_c}\frac{2(Q+q)}{r}dr+\int_{r_w}^{r}\frac{2Q}{r}dr,$$

where r_c and r_w are the radii of the counter cathode and wire, respectively. If c is the capacity per unit length of the counter,

$$c=\frac{1}{2\log(r_c/r_w)},$$

and

$$V=Q/c+2q\log(r_c/r). \tag{2}$$

Let C_1 be the capacity of that portion of the wire not surrounded by the positive ion sheath, together with the other bodies attached to the wire, and let Q_1 be the total charge on them. Then we also have

$$V=Q_1/C_1. \tag{3}$$

If the electrons which were formed in the counter have been collected, then we have a relation between the charges:

$$Ql+Q_1=V_0(cl+C_1)-ql. \tag{4}$$

We can eliminate Q and Q_1 from (2), (3) and (4) and obtain

$$V=V_0-2q\left(\frac{\log r/r_w}{1+(C_1/cl)}\right). \tag{5}$$

The time at which the ion sheath is at a distance r from the counter axis may be written

$$t=\int_{r_w}^{r}\frac{dr}{dr/dt}.$$

Using (5) we may express t in terms of the potentials:

$$t=\int_V^{V_0}\frac{r_w(cl+C_1)}{2qcl}\,\frac{\exp\left[\frac{cl+C_1}{2qcl}(V_0-V)\right]}{dr/dt}\,dV. \tag{6}$$

[5] See, for example, A. V. Hersey, Phys. Rev. 56, 908, 916 (1939).

If we knew the mobility of the ions, we could express the velocity, dr/dt, in terms of the field strength E and hence in terms of V, and our problem would be completely solved. Lacking this information, we must assume some functional form for dr/dt. Let us take, for example,

$$dr/dt=\alpha E^{\lambda}, \tag{7}$$

and obtain an expression for E from (3), (4) and (5). Then,

$$\frac{dr}{dt}=\alpha\left[\frac{2V_0(cl+C_1)-2VC_1}{lr_w}\right]^{\lambda}\exp\left[-\lambda\frac{cl+C_1}{2qcl}(V_0-V)\right],$$

and

$$t=\frac{l^{\lambda}r_w^{1+\lambda}}{\alpha}\left(\frac{cl+C_1}{2qcl}\right)\int_V^{V_0}\frac{\exp\left[(1+\lambda)\dfrac{cl+C_1}{2qcl}(V_0-V)\right]}{[2V_0(cl+C_1)-2VC_1]^{\lambda}}dV. \tag{8}$$

If λ is not too large we may write

$$t=\frac{l^{\lambda}r_w^{1+\lambda}}{\alpha}\left(\frac{cl+C_1}{2qcl}\right)\frac{1}{[2V_0(cl+C_1)-2V_1C_1]^{\lambda}}\int_V^{V_0}\exp\left[(1+\lambda)\frac{cl+C_1}{2qcl}(V_0-V)\right]dV,$$

where V_1 lies between V and V_0 and is close to V. We can now integrate and obtain

$$t=\frac{l^{\lambda}r_w^{1+\lambda}}{\alpha(1+\lambda)}\frac{1}{[2V_0(cl+C_1)-2V_1C_1]^{\lambda}}\left(\exp\left[(1+\lambda)\frac{cl+C_1}{2qcl}(V_0-V)\right]-1\right). \tag{9}$$

We make no serious error by taking $V_1=V$. For $\lambda=0$ the approximation is exact; for $\lambda=1$ the exact integration, with the insertion of appropriate values of the constants, gives a result which differs from the above approximation by less than 5 percent over the ranges of variation considered here. This is precisely the same form that Ramsey finds empirically to represent his results as expressed in Eq. (1). A comparison allows us to evaluate the empirical constants, and since $cl+C_1=C$, we have

$$k=2qcl/(1+\lambda), \tag{10}$$

and

$$t_0=\frac{r_w^{1+\lambda}}{\alpha(1+\lambda)}\left[\frac{l}{2V_0C-2V_1C_1}\right]^{\lambda}. \tag{10a}$$

Thus q and therefore k depend only on V_0, and t_0 is independent of V_0 if λ is sufficiently small. The observations represented in Ramsey's Figs. 4 and 6 indicate that λ is about 0.2, and hence t_0 is very nearly a constant. It might seem that Eqs. (10) and (10a) merely replace the two parameters, k and t_0, by three others: ql, λ and α, so that we have gained nothing by these calculations. Actually this is not so, and therein lies the whole importance of the present interpretation. According to the mechanism outlined above, if the wire potential is below a certain critical value at the time the ions reach the cathode, any electrons that may be formed do not multiply greatly and hence do not contribute to the change of potential of the wire. The calculations given here allow us to find this time. The maximum value of V_0-V is given by

$$V_0-V=ql/C$$

and if this be substituted in expression (9), we find that the time, t_m, at which the ions reach the cathode is given by

$$t_m=t_0[(r_c/r_w)^{1+\lambda}-1].$$

t_m may be determined from the experiments by an extrapolation of the lines in Ramsey's Figs. 4 and 6 until they reach the maximum value of V_0-V. It is to be noticed that all the lines in Fig. 6B and the lines for the four lowest capacities in Fig. 4B agree, within the accuracy of the measurements, in giving the same t_m of a little less than 10^{-5} second, as they should if our picture is correct.† In the case of the two largest

† The values of t_m given above represent the actual times of traversal of the positive ions only if the assumed varia-

capacities, we note that $V_0 - V$ has not attained its maximum value at this time. We therefore conclude that further multiplication must take place. Since V at this time is still above the starting potential of the counter, any electrons ejected from the cathode by the positive ions can still multiply themselves by large amounts, and we will have a repetition of the original process. We therefore conclude that the critical potential is close to the starting potential of the counter, as we should expect. The observations upon other counters under different conditions reported by Ramsey all seem to satisfy equally well the requirements of the picture that we have described.*

The particular values of the arbitrary constants which best satisfy the observations may, of course, be easily derived. For example, in the case of the top-most line in Ramsey's Fig. 4B, the constants taken from experiment are

$$t_0 = 3.5 \times 10^{-8} \text{ sec.}, \quad t_m = 1.2 \times 10^{-5} \text{ sec.}, \quad k = 1.98 \text{ e.s.u.}$$

The constants in our calculated expression derived from these are

$$\alpha = 2.5 \times 10^4 \text{ e.s.u.}; \quad \lambda = 0.2; \quad ql = 11.6 \text{ e.s.u.}$$

Likewise, from the series of observations at different pressures, where the potentials were chosen to give the same value of ql (i.e., the same pulse size), it can be shown that both α and λ increase with increasing pressure. We do not wish to emphasize particularly this feature of the calculations. It does give us some information about the motion of the ions in high fields, but under very special conditions. It is quite possible that the velocity of the ions calculated in this manner is not equal to the product of the mobility and the field strength at each point in the counter. The field is such a rapidly varying function of the distance that the ions may not reach a steady state. If this be the case, the field dependence of the ion velocity is not given by (7) in general, and the assumption of this particular form should be interpreted as the expression equivalent to the assumption that, for our particular field distribution, the velocity varies as $r^{-\lambda}$.**

4. Breakdown Measurements of Other Observers

We may notice from the above discussion of Ramsey's experiments that there are two distinct types of potential variation occurring in a counter. If the potential is high, and the capacity low, the potential will change rapidly, and the change will be complete in the time necessary for one traversal of the positive ions across the counter. When this is the case, the wire potential is below the starting potential at its minimum value. If the capacity is high, the wire potential will be above the starting potential when the first spurt of ions reaches the cathode. The discharge will then not be completed in the first stage, and the time necessary for the wire potential to reach its minimum value will be longer. Thus we have inseparably connected two phenomena: a fast breakdown is always associated with a pulse size greater than the difference between the original potential and the starting potential. This latter phenomenon, which may be termed "overshooting," was first recognized by Medicus,[6] and its existence has been both doubted and confirmed many times. Danforth,[7] of this laboratory, showed that the amount of overshooting decreases with increased capacity of the counter wire. This probably explains why some observers did not find the phenomenon, as quite often large capacities were connected to the wire. Medicus reports that the time of breakdown of his counters was less than 10^{-5} second, in agreement with Ramsey's observa-

tion of the velocity with field strength is also valid in the region of low field strength near the cathode. This is probably not the case, and the actual times of traversal are probably longer. t_m will however be proportional to the true traversal times, and the validity of the arguments presented here will be unaffected.

* We omit from consideration such phenomena as are represented by the secondary "breaks" in Ramsey's Fig. 4B, since the experimental evidence for their existence appears to be still uncertain. It may be noted, however, that when the wire capacity is large, the field in the neighborhood of the wire may be sufficiently high so that, if additional ion pairs were formed in the counter *before* the positive ion sheath has reached the cathode, the electrons so produced would be able to multiply and produce a break of this kind.

** Observations made subsequent to these considerations indicate that the quantity ql is not strictly independent of the capacity of the wire. This does not alter the picture of the discharge mechanism presented here, but suggests an interesting extension of the picture in regard to the propagation of the discharge along the length of the counter. See footnote added in proof to W. E. Ramsey's paper.

[6] G. Medicus, Zeits. f. Physik **74**, 350 (1932).

[7] W. E. Danforth, Phys. Rev. **46**, 1026 (1934).

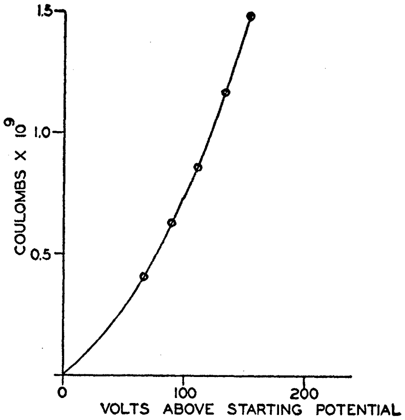

FIG. 1. The amount of charge formed in a counter which overshoots, as a function of the potential above the starting potential applied to it.

tions. On the other hand, Trost[8] reported some oscillographic measurements of breakdown of counters (also not containing an organic vapor) which took up to 10^{-3} second to come for completion. However, Trost's measurements were made with a capacity of nearly 50 centimeters connected to the wire. Presumably, therefore, Trost's counters did not overshoot and the discharge was made up of many stages. It is possible from the calculations presented above and Ramsey's observations to show in greater detail just what is taking place in the latter case. Let us consider the case of the counter 15 cm long filled with argon-oxygen mixture at 9 cm pressure when the capacity of the wire is 63 $\mu\mu$f. The initial portion of the breakdown has been measured by Ramsey and is shown as the lowest curve in his Fig. 4B. The counter wire was initially 157 volts above the starting potential. After the first spurt of ions had crossed the tube the wire potential was still 89 volts above the starting potential. Hence the electrons ejected by the ions from the cathode would be multiplied to a large extent. Just how much charge was formed at this second stage may be obtained from Ramsey's observations of the maximum voltage change of the wire as a function of the wire potential. These observations are represented in Fig. 1. From this charge we can find the potential of the wire after the *second* spurt of ions had crossed the tube, and again from Fig. 1 the amount of charge formed in the third and succeeding stages. In this way we can construct the discharge curve shown in Fig. 2. If we employ an oscillograph and photograph this phenomenon, we shall obtain a record only when the spot is not moving too rapidly and we have attempted to indicate the appearance of the photograph by shading in the figure. The striking similarity of this figure to the photographs of Trost, particularly those on pages 424 and 425 of his paper, seems to be quite convincing evidence of the essential correctness of the picture of the mechanism presented here.*

The recently reported experiments of Shive[9] on the modulation of Geiger counters furnish further confirmation of this picture. Shive's counter A does not overshoot and has a long breakdown time. With his counter B, Shive observed the transition from a slow breakdown to a fast one as the potential on the counter was increased, and at the same potential at which the counter began to have a fast breakdown it began also to overshoot. Thus Shive's observations are in precise agreement with our expectations. However, Shive interprets his observations in terms of two distinctly different mechanisms of counter action, an interpretation with which we must disagree.

5. The Quenching Mechanism

One of the aspects of counter behavior most difficult to understand, if one may judge correctly from the volume of discussion in the literature concerning it, is the means by which the counter discharge is stopped after it has been initiated by an ionizing ray. The considerations of Section 2 allow us to make a more detailed examination of the phenomenon. It is evident that the initial multiplicative process of the formation of electrons by collision must be accompanied by the building up of a positive spcae charge in the neighborhood of the wire. We have postulated that this space charge is sufficiently large to terminate the production of new electrons until the space charge has moved away. Thus at this point we may say that the

[8] A. Trost, Zeits. f. Physik **105**, 399 (1937).

* W. E. Ramsey has recently obtained a series of oscillographs which show the multiple character of the discharge process very beautifully. They will be published soon in the *Journal of the Franklin Institute*.

[9] J. N. Shive, Phys. Rev. **56**, 579 (1939).

first stage of the discharge is already quenched. This quenching has been accomplished before the positive ions have moved away from the wire, and hence before the potential of the wire has appreciably changed. This action of the space charge has been invoked by other investigators, principally by Trost[8] who applied it to explain the action of counters containing alcohol or other organic vapor. We generalize this to apply to other counters, and particularly to the type of counter investigated by Ramsey. As the positive ions move outward, the wire potential will change in the manner calculated in Section 3. We must now distinguish two cases. In the first case, either no additional electrons are produced when the positive ions strike the cathode, which seems to be the case with counters containing organic vapors,* or the wire potential is at this time below the starting potential, that is, the counter overshoots, so that the additional electrons which are produced are unable to multiply appreciably. In this case the whole process is now complete, and the wire will recover its original potential by the leakage of charge across the high resistance connected to it. In the second case, the wire potential is still above the starting potential when the first spurt of positive ions ejects electrons from the cathode and the discharge will proceed by successive stages as shown in Fig. 2. It is evident from Fig. 1 that if the first stage of the discharge is insufficient to bring the wire below the starting potential, no succeeding stage can do so. The successive spurts of charge become smaller and smaller, and the potential of the wire will asymptotically approach the starting potential. The number of electrons ejected by each spurt of ions likewise becomes smaller, and the probability that no electron be ejected by the ions at any one stage becomes larger. When no electron is ejected, the process will, of course, be terminated. That a statistical process is important in counter behavior has been postulated by several investigators[10] independently, although in each case somewhat different points of view have been adopted. The observations of Danforth[7] make very obvious the statistical nature of the time of discharge when large capacities are connected to the counter wire. We may perhaps summarize these points by stating in the usual jargon that "all counters are self-quenching if they overshoot, and if they do not, the inherent instability of the discharge will cause the discharge to be extinguished."

The action of the various vacuum-tube quenching circuits[11] is quite easily understood when considered from the point of view pictured here. The electrical circuit is so arranged that the initial portion of the voltage change of the wire is amplified and the wire potential made to change by a larger amount. If sufficient amplification is employed it is always possible to have the wire at a potential below the starting potential when the first spurt of positive ions reaches the cathode. Thus the series of spurts is broken and the counter then recovers.

It is unfortunate that the term "quenching resistance" has been applied to the high resistance customarily attached to the counter wire. It is obvious that the resistance actually hinders the stopping of the discharge by allowing charge to leak across it, and so helping the wire to maintain its original potential. It would be more nearly correct to say that the discharge stops in spite of the resistance. The true purpose of the

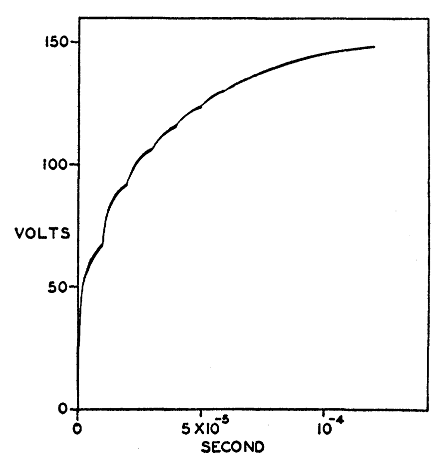

FIG. 2. Discharge curve of a counter with a large capacity connected to the counter wire.

* It should be remembered that counters containing organic vapors are generally operated at a potential below that at which a steady discharge is possible, while other counters are operated at potentials above this point.

[10] A. Nunn May, Proc. Phys. Soc. London **51**, 26 (1939); C. van Geel and J. Kerkum, Physica **5**, 609 (1938); R. Schade, Zeits. f. tech. Physik **19**, 594 (1938).

[11] T. H. Johnson, Rev. Sci. Inst. **9**, 218 (1938), and references given therein.

resistance is, of course, to allow the counter wire to recover to its original state *after* the discharge has stopped. There is one empirical fact in this connection that can easily be explained according to the above considerations. It is commonly known that a counter with a cylinder of large diameter generally requires a higher "quenching resistance" for satisfactory performance than one with a small cylinder. With a cathode of large diameter, the positive ions take a longer time to cross from the wire so that the potential of the wire must not be allowed to recover for a longer time, and this is accomplished by the use of a higher leakage resistance.

One result of these considerations has an important practical significance. It may be difficult or impractical in some cases actually to measure the speed of breakdown of a counter. However, if we merely assure ourselves that the counter wire is falling somewhat below the starting potential with each discharge, then we can be sure that the discharge is quenched after the first stage, and we will have a clean, fast pulse. On the other hand, a counter which overshoots may take a longer time to recover to the state where it is again sensitive than one which does not, so that the overshooting should be a minimum.

6. Further Consequences of the Discharge Process

The mechanism of the discharge process which we have outlined here leads us to several additional conclusions. We should expect, for example, that a continuous discharge taking place in a counter is in reality made up of a series of spurts of charge, each spurt following the preceding one by a time equal to the time of passage of a positive ion across the counter. That the current is subject to large fluctuations has, of course, long been recognized. As the potential across a counter in which a continuous discharge is taking place is reduced, the average current decreases until, at a more or less sharply defined potential, the discharge becomes unstable and the current falls suddenly to zero. We should expect that, at this minimum potential which will just maintain the continuous discharge current, the number of new electrons ejected from the cathode by each spurt of ions will be of the same order of magnitude in all counters. This must be the case, since it is the smallness of this number of electrons that allows the statistical fluctuations in it to be important, and these fluctuations are responsible for the instability of the discharge. The average number of electrons per spurt of ions should be proportional to the number of ions in the spurt, and hence this latter number should depend only upon the surface condition of the counter cathode and the kind of gas. We should expect it, for example, to be independent of the pressure, in the first approximation. The average value of the minimum stable current would then be equal to the amount of charge per spurt divided by the time, t_m, of a positive ion traversal. This expectation may be tested by the observations shown in the first four columns of Table I. The counters used for these observations were the same ones used by Ramsey for his measurements, and the values of t_m were taken from his breakdown observations. Furthermore, we might expect that the resistance of the discharge, defined as the change in potential per unit change in the discharge current, at the minimum potential at which the discharge is stable should be proportional to t_m. The measured resistances are also given in Table I. It is evident that our expectations are well confirmed. Indeed, it is surprising that such an overly simplified model gives such good agreement with experiment.

It has been pointed out by Werner[12] and later by many others that it is desirable to employ a counter having a large value of the minimum steady current. This is customarily explained in the following manner. In order to allow a counter to recover quickly, it is desirable to have a low leakage resistance. On the other hand, the width of the voltage plateau over which the counting rate is almost constant is limited by the fact that at potentials above some critical value, V_M,

Table I. *Data on discharge of counters.*

P cm Hg	Minimum current μa	t_m μ sec.	Charge per spurt coul. $\times 10^{12}$	R megohms	t_m/R Farads $\times 10^{12}$
3	3.3	6	20	1.5	4.0
6	2.3	8	18	1.6	5.0
9	2.0	9.8	20	1.9	5.2
12	1.7	10.6	18	2.1	5.0
15	1.5	13	20	2.6	5.0

[12] S. Werner, Zeits. f. Physik **90**, 384; **92**, 705 (1934).

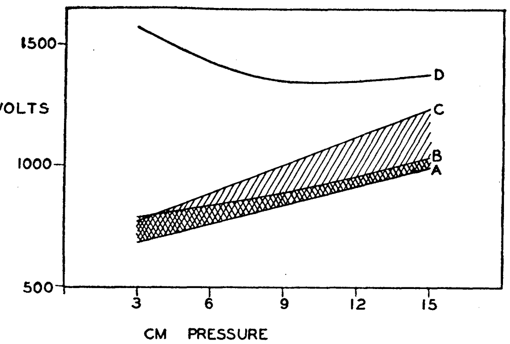

FIG. 3. Diagram showing the operating potentials of counters, with various leakage resistances and wire capacities, as a function of pressure. See text and Table II.

a steady discharge may be maintained across the counter with the resistance in series. V_M is given by

$$V_M = V_{\min} + Ri_{\min}, \tag{11}$$

where $V_{\min}$ is the minimum value of the potential across the counter which will maintain the steady current, $i_{\min}$, in the absence of a resistance, and R the external leakage resistance. Hence if V_M is to be large, $i_{\min}$ must be large. Now in view of the postulated discharge mechanism this may be restated in a somewhat different way. In fact it may be said that it is desirable to have $i_{\min}$ large, since this means that the amount of charge produced in one stage of the discharge is large. Consequently it is easier to attain the desirable condition that the counter is just beginning to overshoot, and as explained above this insures that the pulses will be clean and sharp. The factor which actually limits the width of the voltage plateau of a counter is the occurrence of spurious counts.[13]

It should be emphasized that it may be quite misleading to attempt to predict the behavior of a counter from a knowledge of the steady state conditions, since the time during which a count occurs is too short to allow the establishment of a steady state. In fact, even the condition symbolized by Eq. (11) has no real bearing on the maximum voltage which may be applied to a counter. Eq. (11) merely states that, if a steady discharge is maintained, then the potential applied to the counter must be greater than V_M. It says nothing to the effect that there must be a steady discharge under these conditions. Indeed, if we operate a counter with a low wire capacity, so that it overshoots greatly, then it should be possible to operate it with a very much smaller leakage resistance than usual. As long as the recovery of the wire potential is slow enough so that the potential is below the starting potential at the time the ion sheath reaches the cathode, the discharge will be complete in the first stage regardless of the condition expressed by Eq. (11). If the steady-state condition is in some way attained, the discharge will, of course, continue if (11) is violated. We find, for example, that the counter 15 cm long and filled with 9 cm of argon-oxygen mixture has a minimum current of 1.4 microamperes. Its starting potential is 785 volts. From Eq. (11) we find V_M to be 827 volts for R equal to 30 megohms, or an operating range of only 42 volts. Actually if the capacity of the counter wire is kept small (less than three cm), the counter can be made to operate over a range of almost 300 volts with this value of the resistance. If the capacity is large, the working range is reduced to about 40 volts, as expected. The limit for the low capacity was determined by raising the potential until the counter frequently broke over into a steady discharge. When this occurred, it was necessary to stop the discharge by removing the potential momentarily. The transition to the steady state takes place if a count occurs after another one in the time interval after the wire potential has recovered above the starting potential, and before it is sufficiently high again so that the discharge will overshoot. The upper limit therefore depends upon the counting rate of the counter and is not at all precisely defined. If the counting rate is small and consists only of that caused by the normal background of cosmic rays and the natural radioactivity of the surroundings, a very long time (several hours) may elapse until a

[13] Spurious counts, or the "self-excitation" of a counter, seem to be well explained by the occurrence of a sensitive condition of the surface of the cathode from which are emitted electrons when an electric field is present. See, for example, R. Schade, Zeits. f. Physik **104**, 500 (1937) and H. Paetow, *ibid.* **111**, 770 (1939). This phenomenon has received considerable attention in connection with the problem of why neon glow lamps start, but the results of the investigations are equally applicable to the self-excitation of counters. Spurious counts are thus more or less unrelated to the normal discharge process. They, nevertheless, are an important factor in the "goodness" of a counter, and the technique of the preparation of good counters should insure that they are present to a negligible extent.

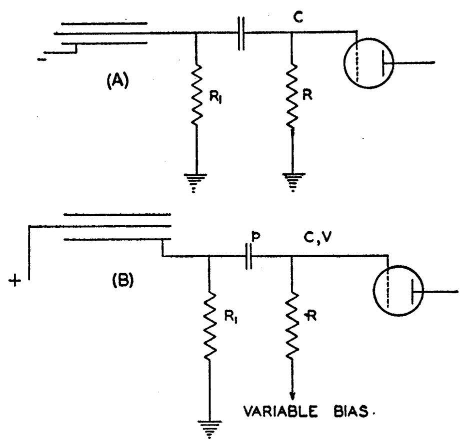

FIG. 4. (A) Circuit diagram showing the usual method of using a counter. (B) Circuit diagram showing an indirect method of determination of counter breakdown times.

discharge occurs in the required interval to create a steady state. As the potential of the wire is raised, spurious discharges begin to occur at a certain value of the potential in numbers which increase very rapidly with potential. This potential is then approximately the upper limit of the region where the counter operates for an appreciable time with a low resistance. The relations between the various quantities are perhaps better illustrated by reference to Fig. 3. The same group of counters, filled with different pressures of argon-oxygen mixture, were used here as for the former observations and those of Ramsey. Curve A represents the minimum potential which will support a steady discharge with zero resistance in series with the counter. This is, within about five volts, also the starting potential of the counters. Curve B represents the minimum potential necessary to support a discharge when 30 megohms are in series with the counter, and was obtained by inserting measured values in (11). If the capacity of the counter wire is large, so that the counter does not overshoot, then the working range of the counter is represented by the double hatched area between A and B. Curve D represents the minimum potential for a steady discharge through a series resistance of 260 megohms. However, spurious counts will be copious at potentials below curve D, and the working range of the counter will be determined by them. Curve C represents, as a function of pressure, the potentials at which the rate of occurrence of spurious counts is equal to the normal counting rate of the counter. Thus the single hatched area between A and C represents the working range of counters with the high leakage resistance. This area will also represent, somewhat arbitrarily of course, the operating range of the counters with a resistance of 30 megohms when they are used with the capacity of the wire at a low value, and this is confirmed by direct test. Table II indicates more concisely, in reference to Fig. 3, the operating ranges of the counters used with the different values of the external resistance and capacity.

The use of a counter in this way with a low resistance and capacity does not form a very practical arrangement for making measurements, but the fact that it can be done seems to be a very striking demonstration of the essential correctness of the discharge mechanism that has been outlined above.

7. An Indirect Method of Breakdown Time Measurement

An approximate method for testing the speed of breakdown of a Geiger counter has been in use for many years. It consists in lowering the value of the resistance R, Fig. 4 (A), until pulses are beginning to be lost even when there is considerable amplification in the remaining stages of the recording circuit. It is then obvious that the order of magnitude of the time of breakdown of the counter is RC, where C is the capacity of the grid of the vacuum tube. Such a method cannot be made precise, since the critical value of R depends upon other factors besides the speed of breakdown. A. Trost[8] has reported observations of the size of the voltage pulse from a counter containing alcohol vapor as a function of the resistance R_1, and has derived from these the values of the counter current as a function

TABLE II. *Operating range of counters.*

External Resistance	Counter wire capacity	Operating Range in Fig. 3	Upper limit of operating range determined by
low	high	between A and B	continuous discharge
high	high	A and C	spurious counts
low	low	A and C	spurious counts causing continuous discharge
high	low	A and C	spurious counts

of time, although the exact manner in which this was done was not made completely clear. This method, besides being limited to counters operated below the potential necessary for a steady discharge, is open to the objection that for low values of R_1 the wire potential does not change with time in the same manner as for high values of R_1, that is to say the method of measurement strongly affects the quantity being measured.

We wish, therefore, to outline a manner of taking observations and of deriving the breakdown characteristics of counters which is not open to this objection. The simplicity of the arrangement should enable wide application to be made of it. Let us consider the circuit represented in Fig. 4 (B). It will be obvious that the analysis given below will be applicable to many other circuits for accomplishing the same purpose. Let C and V be the capacity and potential of the grid of the vacuum tube and the bodies connected to it, and let q be the charge on that system. If $-p$ is the coefficient of induction of the counter cylinder to the grid system, and V_1 is the potential of the cylinder, then we have

$$q = -pV_1 + CV \quad \text{and} \quad \dot{q} = -V/R. \qquad (12)$$

If p is much smaller than the capacity of the cylinder, then changes in V will not affect V_1 appreciably and we can neglect them. By varying the bias on the vacuum tube, it is possible to determine the value of V when it is a maximum, as a function of the resistance R. Let us call this value V_m, and the time at which it occurs t_m. It is easy to show from (12) that

$$\dot{V}_1(t_m) = V_m/Rp \quad \text{and} \quad t_m = RC\frac{d(\log V_m)}{d(\log R)}.$$

TABLE III. *Observed values of R and V_m and computed values of t_m and $\dot{V}_1$.*

R MEGOHMS	V_m VOLTS	t_m MICROSECONDS	$\dot{V}_1$, VOLTS PER SECOND
30	18.5	126	4.1×10^6
5	13.5	22	1.8×10^6
2	12.0	8.9	4.0
1	11.0	4.9	7.3
0.2	7.5	1.4	2.3×10^7
0.1	6.0	1.3	4.0
0.05	4.0	0.68	5.3
0.03	3.2	0.44	7.1
0.02	2.5	0.38	8.3
0.01	1.0	0.48	6.7

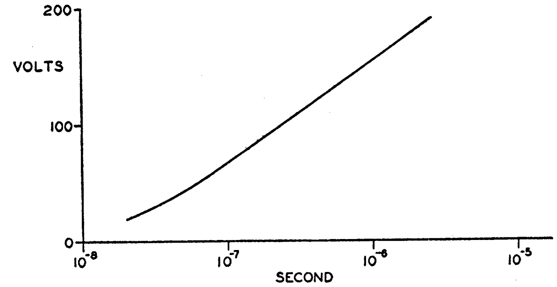

FIG. 5. The potential change of a counter wire as a function of time, determined by the indirect method indicated in Fig. 4(B).

We can integrate $\dot{V}_1$ as represented by these parametric equations, and obtain V_1 as a function of time, which is the desired result. It is well to point out that p may be easily determined experimentally by observing the change in V when V_1 is changed, when R and R_1 are very large. Since q is unchanged by this, $p = C\Delta V/\Delta V_1$. As an application of this method, we may employ some unpublished observations of W. E. Ramsey and D. B. Cowie made in 1934. We wish to express here our appreciation to Messrs. Ramsey and Cowie for allowing us to use these observations. The counter used was 3 cm long and 1 cm in diameter, with a 0.003-inch tungsten wire anode and oxidized copper cathode, filled with 8 cm of argon-oxygen mixture. The value of C was 15×10^{-12} farad and p was 1.5×10^{-12} farad. Table III gives the observations and the values of t_m and $\dot{V}_1$ computed from them. V_1 as a function of time is represented in Fig. 5. The result is in excellent agreement with the direct observations of Ramsey as to the form of the functional dependence of V_1 on t represented in Eq. (1).

8. CONCLUSIONS

We have described in considerable detail a mechanism of the discharge process in Geiger counters and shown some of the consequences to which the picture leads. It seems fitting to append a list of things which remain unsettled regarding counter behavior. The first and most important of these questions has to do with the details of the process by which the charge is built up, and what factors determine how much charge is formed. Likewise much remains to be told in regard to the occurrence of spurious counts and the exact processes there involved. More work is also necessary to explain the time lags between the change of potential of the counter wire and the passage of the ionizing ray through the counter.[14] Also our attempts to explain counter phenomena impress us with the lack of information available regarding the mobilities of ions and electrons in high fields. Finally we must make the large reservation that other varieties of counters may not behave in the same manner as those with which we have worked.

In conclusion, we wish to express our great indebtedness to all the members of the Bartol Research Foundation for allowing us the benefit of their discussion and experience on many points.

[14] C. G. Montgomery, W. E. Ramsey, D. B. Cowie and D. D. Montgomery, Phys. Rev. **56**, 635 (1939); J. V. Dunworth, Nature **144**, 152 (1939).

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Composition of Mixed Vapors in the Cloud Chamber

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The composition of the alcohol-water vapors commonly used in cloud chambers differs from that of the liquid mixtures from which they are produced. This must be considered when ranges or cross sections are to be calculated. Curves are presented for the case of ethanol and water, showing, for various temperatures, the vapor pressure of each constituent as a function of the percent volume of alcohol in the liquid. Attention is called to errors incurred if the cycle of operation is so brief that the vapors do not come up to equilibrium concentration between expansions.

WHENEVER ranges or cross sections are to be determined from cloud-chamber data, it is necessary to know the density and composition of the vapor-laden gas in the chamber at the instant when the ion-trail is formed. Thus we must consider (1) the time required to secure effective equilibrium between the vapor and the liquid on the walls, and (2) the composition of the vapor.

1. Effective thermal equilibrium between walls and gas is established rather rapidly after compression. Kurie[1] found by thermocouple measurements in an 18-cm chamber that the temperature of the chamber gas returned to within 0.1°C of room temperature in 40 to 50 seconds after an expansion or a compression. On the other hand, in large chambers the vapor pressure may remain below equilibrium for a long time. Diffusion is slow and convection depends on temperature gradients in the walls, so we cannot make estimates of general utility, but some idea may be gained from observations of Jones and the writers on the effect of shortening the cycle in a chamber 16 cm$\times$5.7 cm. Conditions are excellent with a cycle approximately 40 seconds long. When the duration of the cycle is cut below 30 seconds, keeping the expansion ratio unaltered, the tracks are not well developed. It is evident that many ions fail to produce droplets, for it is possible to arrange conditions so that only the densely ionized ends of electron tracks are seen. With the cycle duration held at a constant value of the order of 20 seconds, conditions get worse as time goes on so that after 8 or 10 cycles no tracks are seen. This deterioration can be combatted to some extent by increasing the expansion ratio. When the normal cycle and normal expansion ratio are re-established, satisfactory tracks are quickly obtained. There can be little doubt that the short cycle makes the chamber vapor-poor.

2. When a mixture of two vapor-producing liquids is employed, the composition of the vapor is not necessarily the same as that of the liquid mixture. The effect is a large one in the case of the commonly used alcohol-water mixtures and should be taken into account in accurate work.

[1] F. N. D. Kurie, Rev. Sci. Inst. **3**, 655 (1932); the mechanism of this recovery was elucidated by E. J. Williams, Proc. Camb. Phil. Soc. **35**, 512 (1939).