THE

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 66, NOS. 3 AND 4 AUGUST 1 AND 15, 1944

Reduction of the Natural Insensitive Time in G-M Counters

J. A. SIMPSON, JR.*

Department of Physics, New York University, University Heights, New York

(Received February 18, 1944)

The limitation on the Geiger-Müller counter insensitive time which is imposed by the presence of the positive ion space charge has been reduced by collecting the positive ions on the counter center wire instead of at the outer cylinder. The electronic circuit which carries out this process is described in detail. A reduction by another order of magnitude in the insensitive time or an insensitive time of about 2×10^{-5} sec. is obtained with no indication that the limit of the new method has been reached. The general properties of an inverse counter are discussed. The mechanism of this mode of counter operation is explained with considerable evidence indicating the presence of three distinct ion collection regions for the negative center wire. A stable circuit useful as a research tool has been devised for use with a large variety of counters.

I. INTRODUCTION

CAREFUL studies have been made[1, 2] of the positive ion sheath which show that there is a natural insensitive or dead time associated with each type of G-M counter. This insensitive time exists because the positive ion space charge reduces the electric field in the center-wire region below the critical value for supporting a new avalanche until the space charge has moved outward about two-thirds of the distance toward the cathode. If a high mobility ion sheath could be formed, this transit time would be reduced considerably. Such a sheath is encountered in a permanent gas mixture of two light gases, but to date no method has been successful in preventing secondary electrons and photons from forming in such a counter. If an attempt is made to use polyatomic gases which have a very small mass and size, then the dissociation process from counting results in continual changes with time of the counter characteristics, and the counter has a very short lifetime.

This insensitive time of G-M counters places a severe limitation on their use in obtaining accurate data at high counting rates. Since, in general, the events which are recorded by such counters are purely random, at high counting rates there will be a large number of intervals between two successive events which are less than the insensitive time interval of any counter. This loss of counts at high rates is expressed in an equation derived by Ruark and Brammer[3] in which the insensitive time is σ; the true counting rate is N_t and the observed rate is N_a; the equation is

$$N_a = N_t/(1+N_t\sigma).$$

In order to obtain some idea of these losses for different values of σ, the family of curves for N_a, $(N_t/N_a)-1$ with σ as a parameter appears in Fig. 1. Some values for σ the order of 10^{-4} second

---

* Now at the University of Chicago, Chicago, Illinois.

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

[2] H. G. Stever, Phys. Rev. 61, 38 (1942).

[3] A. E. Ruark and F. E. Brammer, Phys. Rev. 52, 322 (1937).

have been chosen which agree with experimental values obtained for so-called "fast" counters. The very best conditions that can be obtained in recording data from a counter with insensitive time σ are attained when the amplifier responds to the very tiny pulses which may occur immediately after the elapse of the time interval σ following each ionizing event, unless the counter is operated just below the Geiger threshold. In the latter case, the sheath does not fully develop, and the pulses are not independent of the kind of ionizing event.

A solution to the problem is usually not found by changing the geometry of the sources of the ionizing events during the experiment, especially if the high counting rate is changing rapidly with time. If the source is placed at such a distance that it produces a counting rate low enough to avoid serious losses, then when the source decays rapidly, the counting rate will become so reduced that exceedingly long times are required to maintain the accuracy of the individual measurements.

II. A NEW COUNTER MECHANISM

Another mode of operation of a G-M counter is evidently necessary if progress is to be made in reducing σ. It has been effectively shown by Ramsey[4] that the total collection time for electrons on the center wire of an organic vapor-noble gas counter is less than 10^{-6} second, and most of the electrons are collected in about this time in a "slow" counter. Therefore, after the center wire begins to drop in potential, use is not made of the subsequent cycle so far as recording the event is concerned. Consider an alternative procedure. Instead of allowing the positive ion sheath which forms around the center wire to move outward, suppose these ions were almost immediately collected on the center wire. This may be accomplished by reversing the potentials on the center wire and cylinder long enough to insure collection. Since the ions are formed only in the immediate vicinity of the wire and will therefore be in a high field which accelerates them toward the center wire, this collection time will be very short, probably less than 10^{-5} second. As soon as all ions are collected, the counter should be immediately returned to its normal operating potential to be ready for the next event. In this case the outer cylinder serves only as a field-forming conductor.

It is important to consider the properties and action of a counter when it is inverted. As in the case of the positive center wire, the negative center-wire counter has a definite potential at which it breaks into corona. For the impure gases which exist in G-M counters, the breakdown potential at very low pressures when the center wire is positive is greater than when the center wire is negative. The pressure-potential curves, however, cross at higher pressures, and for pressures used in most counters the breakdown potential of the negative center-wire system will, in general, be greater.[5]

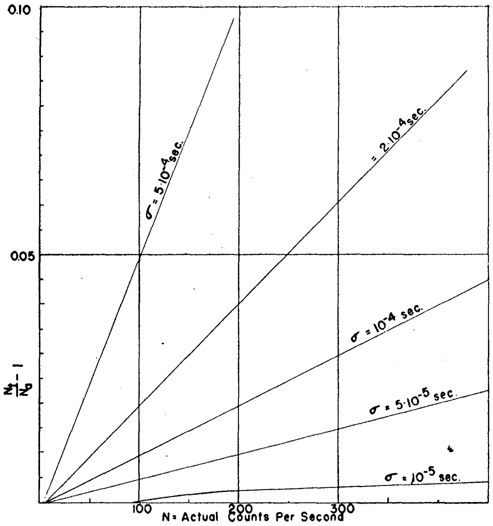


FIG. 1. This is a graph to determine the true counting rate N_t from the observed counting rate N_a for a given insensitive time σ.

Below the breakdown potential in a negative center-wire system there is a small region in which the system behaves like a G-M counter in some respects. An ionizing event in the volume results generally in a single pulse, and the pulse is independent of the number of primary ions produced. This may be called the inverse Geiger region. Counters operated in this fashion have been tried principally by Ramsey and Cowie.[6] However, it

---

[4] W. Ramsey, Phys. Rev. **57**, 1022–1029 (1940).

[5] M. J. Druyvesteyn and F. M. Penning, Rev. Mod. Phys. **12**, 122 (1940). These authors present a complete brief discussion on breakdown and corona with a concentric electrode system.

[6] D. B. Cowie, Phys. Rev. **48**, 883 (1935).

is evident that most ionizing events take place in the outer volume of the counter, and therefore the time before a positive ion reaches the center-wire region is a variable; the positive ion has a very low mobility compared to electronic mobility. As a result, negative wire counters cannot be used in a coincidence circuit. The background of such a counter is high, and it appears to have no appreciable plateau. If the potential is raised slightly, but not enough to cause breakdown, the counter may break into periodic groups of high frequency oscillations. The envelope of the groups is well defined. An explanation of this will be discussed below.

By making the center wire negative, the production of photoelectrons becomes negligible. Photoelectrons are produced at the cathode of the electrode system which in this case is the center wire. Therefore, this photo-effect is reduced by a factor approximately equal to the ratio of the wire radius to the cylinder radius. It should be noted that tungsten, which is widely used for center wires, has a work function of about 4.5 ev.

The behavior of positive ions near the negative center wire for potentials below the inverse Geiger region is probably quite complex and does not lend itself to an exact solution. It is desirable to know under what conditions the positive ions may acquire enough energy to produce secondary electrons by field emission at the wire. If the ions are polyatomic, they may be polarized near the wire and change the effective mean-free-path in that region. At the conclusion of this discussion something will be said concerning these processes in the light of experiments to be presented.

The avalanche process at the negative wire has many characteristics which differ from the well-known positive center-wire avalanche. If a positive ion approaches the center wire and causes the ejection of an electron by field emission, this electron will travel toward the outer cylinder. The field is decreasing as $1/r$. By the time electron avalanche production would be able to increase to very large values, as in an increasing field, the avalanche head has already entered a low intensity field region. Townsend's coefficient α, which is a measure of the number of ion pairs formed by an electron in one centimeter of its path, depends upon the field intensity and the pressure. Since α is decreasing almost exponentially as the avalanche head moves into a region of low E/p, the production will break off fairly sharply. The field is further distorted and reduced by the positive space charge left behind the avalanche. The current flow of electrons, therefore, increases rapidly to a value which is constant for most of the distance out to the cylinder. If many electrons initiate a large number of avalanches, the positive space charge may be sufficient momentarily to choke off further avalanche production until a large portion of the positive ions have been collected; the process then repeats. This would produce an oscillatory discharge in the counter of the nature previously described.

The negative ions play an important part if a great number exist when the counter potentials are reversed, for then the negative ions must travel out toward the cylinder. However, if only a few such ions are formed, they need cause no difficulty because they will not distort the field distribution; they will not lose their electrons in a region where a new avalanche could possibly start. The field in front of the outer cylinder is very low.

These general considerations indicate that the new mode of counter operation proposed can be successful if the proper inverted region is selected. Later, this will be shown to be possible.

III. THE EXPERIMENTAL CIRCUIT

The requirements for the design of an electronic circuit to produce the random reversals at a very high average rate with precision are:

1. The input to any amplifying device which operates on the first three or four volts' drop of the steep pulse front must be insensitive to the process of reversing the field.
2. The circuit must have extremely low RC times throughout; it must respond to frequency components around two megacycles and still possess fairly high gain.
3. The reversal process must be carried out so that not more than a few microseconds elapse before the field is inverted and ions are being collected.
4. No residual voltage "tails" more than three or four volts can be tolerated after collection time

is over or, at high counting rates, the effective operating potential will be changed.

5. Accurate control of the time and extent of the reversal of field must be possible over a wide range to accommodate all types of counters.

6. All supply potentials must be constant under extreme fluctuations of counting rates.

7. The circuit should be constructed from standard equipment available to all laboratories if it is to be of use as a research tool.

A circuit fulfilling these requirements has been developed and operated successfully; before describing it in detail, it would be best to outline the general method with the aid of a simplified block diagram, Fig. 2, representing the circuit elements. Normally no current flows in R_b; therefore the counter is operating at a potential V_2. When the electrons are collected from an ionizing event, a positive pulse begins to form across R. This is detected, and a sharp pulse passes through to the first trigger pair which produces a rectangular wave of time length t_1; this is fed back to the input circuit to act as a shutter preventing the first portion of the circuit from functioning for a time t_1. The second trigger pair is actuated by the incoming pulse also, and it produces a rectangular wave of width t_2. This rectangular pulse is converted to a rectangular pulse approximately $-(V_1+V_2)$ volts high appearing at a. If $t_1>t_2$, then all disturbances on the center wire are over before the shutter opens again.

The schematic diagram of the circuit actually used appears in Fig. 3. All values of the circuit constants are listed. A beam power tetrode of type 807 (or type 829 with its elements in parallel) is used for the high voltage pulse-forming tube with the grid bias of about -150 volts adjusted to place the grid potential beyond cut-off; thus the average plate current required is very low. With the center wire connected directly to the plate of the tube, the full counter operating potential V_2 is applied between ground and plate supply potential. The cathode and heater are $-V_1$ volts below ground potential with V_1+V_2 volts applied across the type 807 tube. The series of pulses to be described appears in Fig. 4A. The positive pulse front a which is several volts high in one or two microseconds appears across the resistor R since the impedance in the plate circuit of the 807 is negligible in comparison with R. Pentode A is biased just beyond cut-off, so it will produce a sharp negative pulse b across its plate impedance when the small positive pulse (1–3 volts) is applied directly to the grid of A. Pentode B amplifies and inverts this pulse c by operating well up on its normal characteristic curve. From here, the positive pulse is applied to the tube C which serves two purposes. It produces a negative pulse d for the trigger pair D and E; it also is used as the shutter for the amplifier by receiving a rectangular wave e from the trigger pair on the biased suppressor grid. The shutter time t_1 is controlled by R_{13}. The trigger pair operates in the conventional manner with tube D normally conducting and with E normally nonconducting. The steep front of the negative rectangular pulse is differentiated f by the circuit $R_{18}C_9$. This triggers the tubes F and G which are arranged exactly as D and E so as to produce a rectangular pulse g whose time width t_2 is determined by R_{18}. The pulse is now amplified by H and inverted h so it can drive the grid of the type 807 so far positive that small variations in the height of h will not affect the characteristics of the negative pulse i of approximate height V_1+V_2 volts. But the outer cylinder of the Geiger counter is near ground potential; therefore the center wire drops to approximately V_1 volts below ground potential. Since the plate circuit has a much lower impedance than R, the differentiated rectangular wave will appear at the input of the amplifier tube A, but a time $t_1>t_2$ must elapse

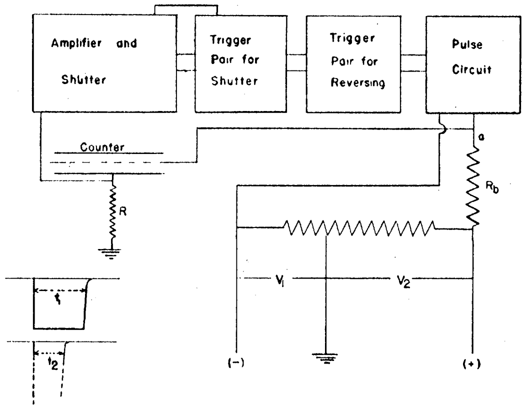


FIG. 2. This block diagram illustrates the manner in which the circuit elements are arranged to produce positive ion collection on the Geiger-Müller counter center wire in order to reduce the counter insensitive time.

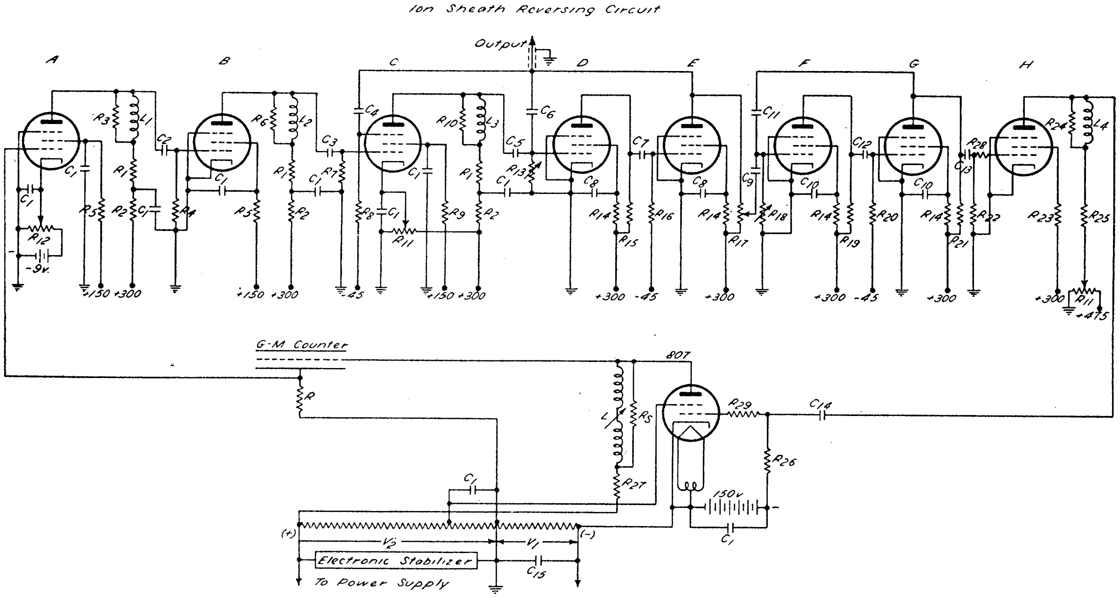


FIG. 3. Schematic diagram of electronic circuit to collect positive ions on the center wire after each ionizing event. The circuit constants are as follows:

C_1 =0.1 μf,
C_2 =50 μμf,
C_3 =20 μμf,
C_4 =0.02 μf,
C_5 =20 μμf,
C_6 =100 μμf,
C_7 =0.02 μf,
C_8 =10 μf,
C_9 =10 μμf,
C_{10}=0.1 μf,
C_{11}=100 μμf,
C_{12}=0.02 μf,
C_{13}=500 μμf,
C_{14}=0.001 μf,
C_{15}=4 μf,
L_1 =1.2 mh,
L_2 =0.67 mh
L_3 =1.2 mh,
L_4 =80 mh,
R_1 =3500Ω,
R_2 =500Ω,
R_3 =25 K,
R_4 =25 K,
R_5 =2500Ω,
R_6 =25 K,
R_7 =0.1 meg.,
R_8 =25 K,
R_9 =2.5 K,
R_{10}=25 K,
R_{11}=75 K w.w.
R_{12}=25 K,
R_{13}=2 meg.,
R_{14}=10 K,
R_{15}=4 K,
R_{16}=50 K,
R_{17}=6 K,
R_{18}=1 meg.,
R_{19}=2 K,
R_{20}=50 K,
R_{21}=6 K,
R_{22}=0.1 meg.,
R_{23}=500Ω,
R_{24}=0.1 meg.,
R_{25}=15 K,
R_{26}=50 K,
R_{27}=4 K,
R_{28}=2500Ω,
R_{29}=500Ω,
R =75,000.

A, B, C, D, E, F G, H are 6AC7.

before the amplifier passes any pulses through the shutter, and so this pulse is unrecorded.

A vertical section through the diagram (Fig. 5) of the potential changes on the counter electrodes as a function of time gives the potential between the electrodes at any instant. The shaded area is drawn between the two electrode potential curves. The first pulse *a* is purposely drawn incorrectly to point out the importance of avoiding "tails" on the pulses. With pulse *a* the counter does not get back onto its operating potential until the tail of the reversing pulse has disappeared. The tiny differentiated pulse appearing at the outer cylinder further tends to reduce the operating potential immediately after ion collection. Pulse *b* is the composite of the two pulses actually observed on the oscilloscope when the circuit is functioning correctly.

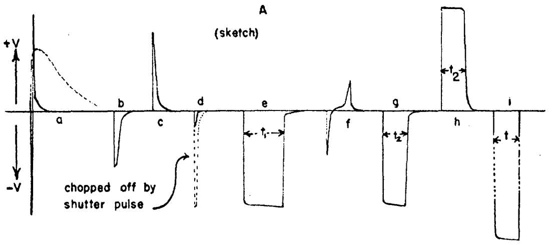
IV. CIRCUIT TESTS

The preliminary testing of circuit elements is of importance. The tubes *A*, *B*, and *C* were overcompensated with inductance to avoid severe losses of the higher frequency components of the pulses by tube and circuit capacities. Such amplifiers must be untuned because of the aperiodic nature of the pulses. The upper frequency limit of the amplifier is many times that of the pulses themselves. The very low frequencies were of no particular concern in this work. Decoupling in the plate circuits is provided wherever it might possibly avoid difficulties. Tests were made with microsecond pulses over a wide frequency range. The power supply for tubes *A* through *H* was a single unit run from a stabilized power line.

The shutter circuit composed of tubes *C*, *D*, and *E* must be carefully adjusted. The biases on the control grid and suppressor grid are so adjusted that the tube is normally just beyond cutoff. A pulse appearing on the control grid is amplified, but a negative rectangular wave applied to the suppressor grid will keep the tube non-conducting. This circuit element is checked by applying sharp microsecond pulses at about 100–200 kc to the control grid while varying the time t_1. By so doing the frequency can be divided by the shutter by any integral factor up to the limit of t_1 determined by tubes D and E. The input to D must be carefully adjusted. Several methods of coupling the pulses from F and G to the type 807 have been tried with success, but the one illustrated was used in obtaining the results described in this paper.

Since the grid is V_1+150 volts below ground, it is essential that C_{14} be a high voltage condenser and that the separate filament transformer be insulated *if* widely varying potentials of V_1 are desired; otherwise, for normal operation no such precautions are necessary. The screen supply voltage may conveniently range from 300–600 v. On counters with low operating potentials a 6C6 tube or equivalent type has worked with some success.

It has already been pointed out that no tail (>3 or 4 v) must be present on the negative 1000 to 1500 v pulses produced by the type 807 tube. If only a plate resistor with the usual small compensating inductance were used, long tails starting about 150–200 v in height appear even with small values of R_b. This problem was effectively solved by means of an LRC circuit. Used with a variable inductance L_s (approximately 15 millihenries), the resistance R is critical and has a value of about 550 ohms. Figure 4B shows the results (not drawn to scale) of varying both the shunting resistance and the inductance. The tail in pulse VI is less than 4 v high above the axis and disappears within the time t_2.



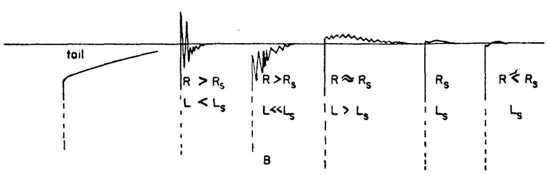


FIG. 4A (Above). The pulse shapes observed on an oscilloscope connected to different portions of the circuit. The pulses are not drawn to scale. The input pulse is the first positive front of a; the reversing pulse is i.

FIG. 4B (Below). The effect of varying the value of the inductance L_s and its shunt resistance R_s on the tail of the reversing pulse. The tail must be very small so that the counter can return to its operating potential rapidly.

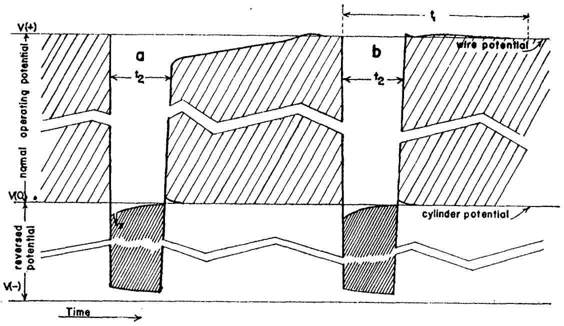


FIG. 5. A graphic illustration which indicates the potential difference between the center wire and outer cylinder of the counter at any instant of the counter reversal process. The shaded areas are drawn between the two electrode potential curves.

The separate power supply for the type 807 is stabilized electronically. Under a load of 100 to 150 milliamperes the voltage should not fluctuate.

By using periodic groups each of two pulses of width 10^{-6} second, spaced 10^{-6} second apart, the circuit is checked for selectivity. The second pulse is eliminated, and the circuit only reverses on the first pulse of each group as it should. The whole circuit has been tested at frequencies over 300 kc with a coupling condenser instead of a counter between tube 807 and the input of tube A which has the same value as the counter capacity.

All observations were made on a Dumont oscilloscope No. 241, a shielded probe, and high impedance attenuator. Care must be taken that the observation does not alter the circuit in any manner. Any oscilloscope whose amplifier characteristics are not flat in frequency response up to 2.5 megacycles should not be used.

The scaling and recording circuit is operated from the output at E. The first scale of 8 or 16 functions up to about 3 megacycles, and the remaining scalers to form a scale of 512 are conventional hard-tube circuits.

To find the time delay in making the center wire V_1 volts negative with respect to ground, the sharp input pulses were superposed with the reversing pulses on the oscilloscope screen. This delay is about 1.5×10^{-6} second for a 1000-v pulse.

V. RESULTS

The reduction of the insensitive time of a G-M counter by this circuit can be determined by any one of several methods for measuring resolving times. The most useful one for instantaneous observation is the single-sweep trigger circuit as used by Stever.[2] One event triggers off an oscilloscope to sweep across the screen; at high counting rates there is a fair probability that the next event will occur near the limit of the insensitive time. This is observed by pulses making their appearance on the screen after the insensitive time interval. Thus, by repetition of the pattern the interval between the trigger pulse and the next appearance of the pulses measures the insensitive time σ. By using this circuit connected to the first or second trigger pair in the reversing circuit, the circuit characteristics will not be changed. All pulses will be of the same height in contrast to the usual observations.[2] These observations have been made with a calibrating time scale (3 percent error) incorporated in the sweep.

Polyatomic-noble gas counters are most useful for the first experiments for two reasons. Whenever the reversing circuit is shut off, the counter will not be destroyed. Also this type of counter has the lowest range of insensitive times used at present, and therefore it is a suitable standard for comparison with results obtained by using the reversing circuit.

The factor of reduction of insensitive time is plotted in Fig. 6 as a function of the magnitude of the reversing potential for the first counters[7] used in the circuit. $\sigma_{-\text{off}}$ is the insensitive time of the counter without the circuit; $\sigma_{-\text{on}}$ is the insensitive time of the counter when the reversing circuit is used. Great care was taken that the smallest pulses would be recorded. For each counter V_2 is a constant. Preliminary experiments indicate that the new insensitive times lie around 2×10^{-5} second. This is nowhere near the limit to be expected in future trials. It should be noted that these values are obtained under very stable conditions; the apparatus may be turned off and warmed up again as desired without difficulty. Background counting rates remain a constant in using the circuit.

In obtaining the points for the curves in Fig. 6 the collection time was adjusted for its optimum value for each value of V_1 with the shutter pulse set at $t_1=1.5\times10^{-5}$ second. The time t_2 varied from 2.5×10^{-6} to about 6×10^{-6} for the ion collection.

Additional tests were made by using two γ-ray sources, one twice the intensity of the other. The intensities of these sources are first accurately determined. Then the lower intensity source (No. 1; 9.98 mg) is determined at, say, 10 counts per second; the second source (No. 2; 19.98 mg) is placed in the same position, and the counting rate is again determined. Finally, with both together the counting rate is obtained. After repeating this procedure at several distances from the counter the information can be used to obtain curves like those in Fig. 1.

By varying the potential and width of the reversal pulse three distinct regions in the inverse Geiger region are found in polyatomic-noble gas counters. This has been anticipated to some extent in the introductory remarks of this discussion. At low voltages (up to about 300 v with counters operating at around 1100 v) the ion sheath is collected within about 7×10^{-6} second without producing any detected secondary effect. The upper limit of this potential is defined within about 40 v, but its magnitude depends upon the counter properties, especially the mean free path at the center wire. The diameter of the center

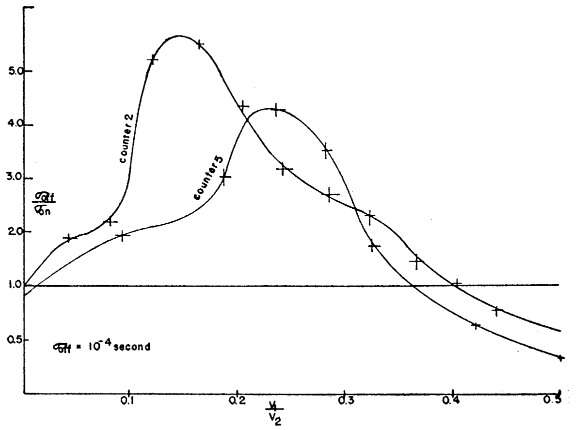


FIG. 6. Experimental evidence of the decrease in counter insensitive time produced by reversing counter electrode potentials for positive ion collection. σ_{off} is the insensitive time with the reversing circuit off; σ_{on} is the insensitive time using the circuit. V_2 is the counter operating potential; V_1 is approximately equal to the reversed potential.

---

[7] Counter No. 2 has 10 percent amyl acetate; 90 percent argon. Counter No. 5 has 10 percent ethyl alcohol; 90 percent argon.

wire will also determine the terminus of the first region. An experiment in which the diameter of the center wire is varied has been planned.

The second region begins when tiny sharp pulses (less than 0.3 v) appear at the outer cylinder about 2×10^{-4} second after the ionizing event *a*. Figure 7 illustrates the changing character of this "tail" as a function of V_1, which appears at the end of the differentiated negative pulse. In each successive drawing the potential V_1 has been increased. It is possible to hazard an interpretation of this phenomenon. In *a* and *b* the small pulses are due to positive ions arriving at the outer cylinder. The beginning of the second region is one in which the noble gas positive ions begin to have enough energy to produce secondary electrons at the center wire; these electrons will produce new local avalanches whenever the field is intense enough to support them. The space charge is being collected before transformation by electron transfer can occur; therefore a considerable portion of the sheath is composed of the noble gas ions. An example of this process appears in the literature. Penning[8] has observed that the number of electrons produced per positive ion impact varies from about 0.03 to 0.05 for ions having energies less than 50 v. This fraction increases nearly linearly with energy up to 0.42 for 1000-v ions.

How are the characteristic patterns of *a*, *b*, and *c* to be explained in view of the fact that the ion collection times can be varied somewhat without changing them? As the positive ion sheath is coming toward the center wire, the field between sheath and wire becomes more intense, but the region beyond the sheath drops to a relatively low value because of this space charge. Secondary electrons passing outward are, therefore, unable to start avalanches in this region. As the sheath is being collected, the field again rises to the point where local avalanches may be produced. The continued collection of the sheath brings new local avalanches closer and closer to the wire. If the counter were suddenly returned to normal conditions at this instant, small individual space charges would move out to the cylinder to be collected, thus producing small peaks in the ion collection pulse. But if the counter were not reversed at this instant, the new positive ions would arrive at the wire to continue the process until the counter potentials were changed. Again the ion collection pulse would be a series of peaks. Little or no spread of the discharge due to photons may be expected in the lower part of this region in which only a few of the positive gas ions have enough energy to produce secondary electrons. The resolution of pulses in *a* and *b* tends to confirm the assumption made in G-M counter theory that the ions move out without much spreading, i.e., the sheath can be treated as infinitely thin for purposes of calculation.

As the potential V_1 is increased, secondary electrons are produced all along the wire while positive ions are being more rapidly removed from the original sheath. A large space charge from the electron avalanches then forms not only around the wire, but also along its length; the role of photons in this process is questionable. The large space charge immediately chokes off further avalanche production, and the large burst of electrons which formed the avalanche shortly arrives at the outer cylinder. The collection of these electrons can be observed by the negative pulse appearing at α in *d*, *e*, and *f*. The magnitude of this pulse is a function of the potential V_1 and not of the counter overvoltage; therefore it cannot be interpreted as a collection of the original positive ions. This pulse is terminated within 4–5$\times10^{-6}$ second from the time of reversal. It demonstrates that the original positive ion sheath is at least mostly collected within that time interval. When the time t_2 is extended, a repetition of the process takes place and a second negative peak is to be observed. When the

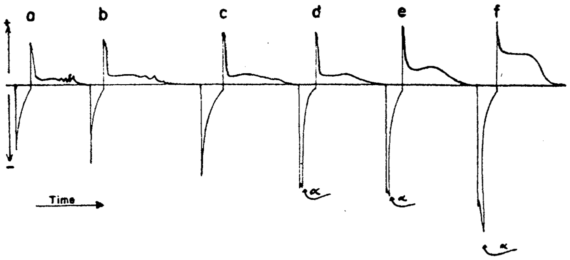


FIG. 7. Sketches of the pulses observed by using an oscilloscope connected to the outer cylinder. The potential V_1 is great enough to cause positive ions to produce secondary electrons at the center wire. V_1 is increasing from left to right.

---

[8] F. M. Penning, K. Akad. Wet. Amst. Proc. **33**, 841 (1930).

counter potentials are returned to normal operating potential, this extensive positive ion sheath moves outward producing the positive hump shown on the tail of the differentiated pulse. A counter operated in such a region obviously has its insensitive time increased rather than decreased.

The negative pulse α and the positive hump continue to increase with the potential of V_1 up to a value $|V_1| \overset{\frown}{=} |V_2|$ where the third region begins. This is the inverse Geiger region described in the introduction. Multiple and spurious pulses make their appearance. Above this potential lies the corona discharge region which is well known and is useless in these observations.

By triggering the reversing circuit artificially in any of these regions at a time when no ionizing event is present, it can be shown that the differentiated pulse lacks all the characteristic pulses described in the preceding paragraphs; the phenomena are due to counter action and not to the characteristics of the reversing pulse. In Fig. 6 the point where the curve crosses the unity axis indicates the vicinity of the boundary between the ion collection region and the region in which ions are beginning to produce secondary electrons.

Another way in which to collect the positive ions at high counting rates may be pointed out. Suppose the circuit reverses periodically, being inverted for a time t' and returning to normal for a much longer time t''. Further, t'' will be made smaller than the normal insensitive time t_d. A complete cycle of operation, therefore, requires a time $t'+t''<t_d$. Conservative values for these times can be chosen, such as

$$t' = 10^{-5} \text{ second},$$
$$t'' = 4\times 10^{-5} \text{ second}.$$

To a first approximation the probability of two events in a random distribution occurring in a time interval less than τ with a counting rate $N/\text{sec.} = 1/\bar{t}$ is[9] $p=\tau/\bar{t}$. Assuming a counting rate of 500 per sec. the probability of two events occurring in a time interval 10^{-5} sec. is 5×10^{-3}, in a time interval 5×10^{-5} is 2.5×10^{-2}, and for 10^{-4} sec. (the dead time of a "fast" normal counter) is 5×10^{-2} sec. The advantage of such a procedure over using the counter alone is further emphasized since it is definitely known that $\frac{1}{5}$ of all the counts are purposely not being recorded.

Although the circuit in Fig. 3 was designed to study the properties and possibilities of reducing the insensitive time, it may be used as a research tool; there are several critical adjustments which have been described, but once adjusted, the circuit is stable. For use with a particular counter type a much simpler circuit may be devised. The gain requirement may be relaxed. A simple design would include two stages of amplification incorporating the shutter along with two *LC* circuits to produce rectangular waves of the desired widths and a pulse amplifier followed by a blocking oscillator using a pulse transformer. The large tail produced by such an oscillator may be corrected by the *LRC* circuit suggested earlier. The use of a high voltage trigger pair to obtain the reversing pulse has the disadvantages of requiring a large average plate current and producing pulses of an undesirable shape. The new techniques which will be available in the future for pulse production may result in a drastic simplification of the reversal circuit. Research is still to be carried out on the permanent gas counter; the advantage of using such a counter is that it should maintain its characteristics until the wire becomes badly pitted. Since the outer cylinder now only assumes the character of a field-forming electrode, serious consideration should be given to the fact that almost any surface layer which does not accumulate charges may be used to make the production of photoelectrons impossible.

ACKNOWLEDGMENTS

The writer wishes to express his sincere gratitude to Professor S. A. Korff for his encouragement and helpful suggestions and to both him and Professor R. D. Present for innumerable discussions which helped to clarify the problem. Thanks are due to Dr. V. C. Wilson for first suggesting the problem and for his continual interest in its development.

---

[9] J. Strong, *Procedures in Experimental Physics* (Prentice-Hall, Inc., New York, 1938).