March 31, 1953 V. C. WILSON ET AL 2,633,540

ELECTRICAL APPARATUS AND METHOD

Filed April 26, 1945 3 Sheets-Sheet 1

FIG. 1.

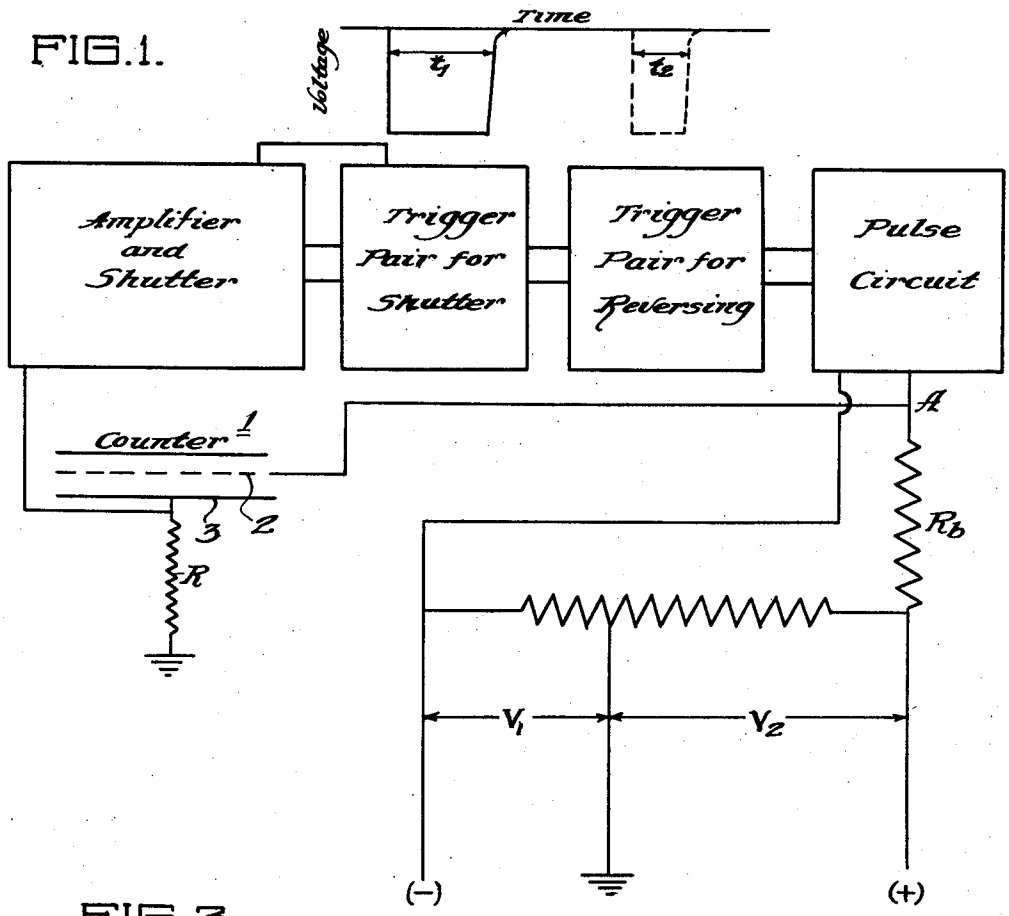
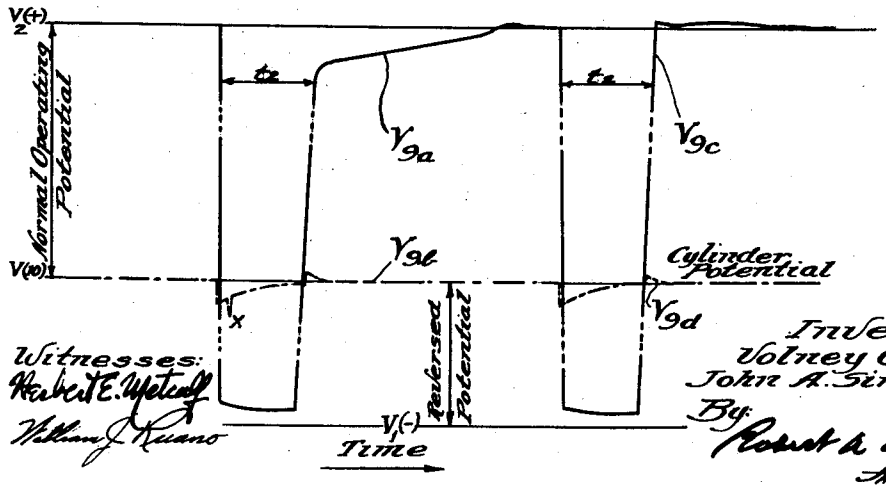


FIG. 3.

The Potential Difference Between Electrodes as a Function of Time



Witnesses:
Herbert E. Metcalf
William J. Ruano

Inventors:
Volney C. Wilson
John A. Simpson, Jr.
By: Robert A. Lavender
Attorney.

March 31, 1953 V. C. WILSON ET AL 2,633,540

ELECTRICAL APPARATUS AND METHOD

Filed April 26, 1945 3 Sheets-Sheet 2

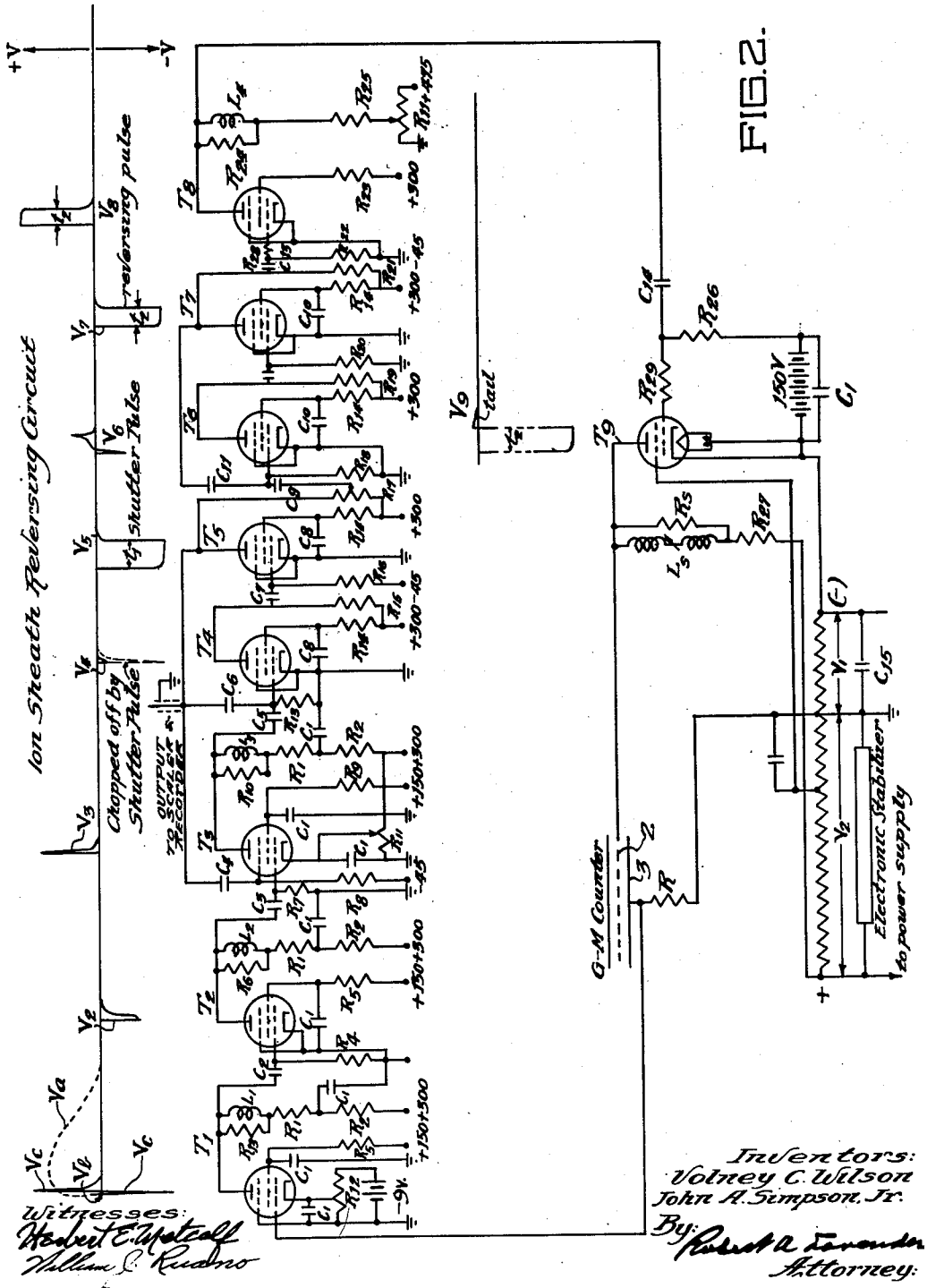


FIG. 2.

Witnesses:
Herbert E. Metcalf
William L. Rudno

Inventors:
Volney C. Wilson
John A. Simpson, Jr.
By: Robert A. Lavender
Attorney:

March 31, 1953 V. C. WILSON ET AL 2,633,540

ELECTRICAL APPARATUS AND METHOD

Filed April 26, 1945 3 Sheets-Sheet 3

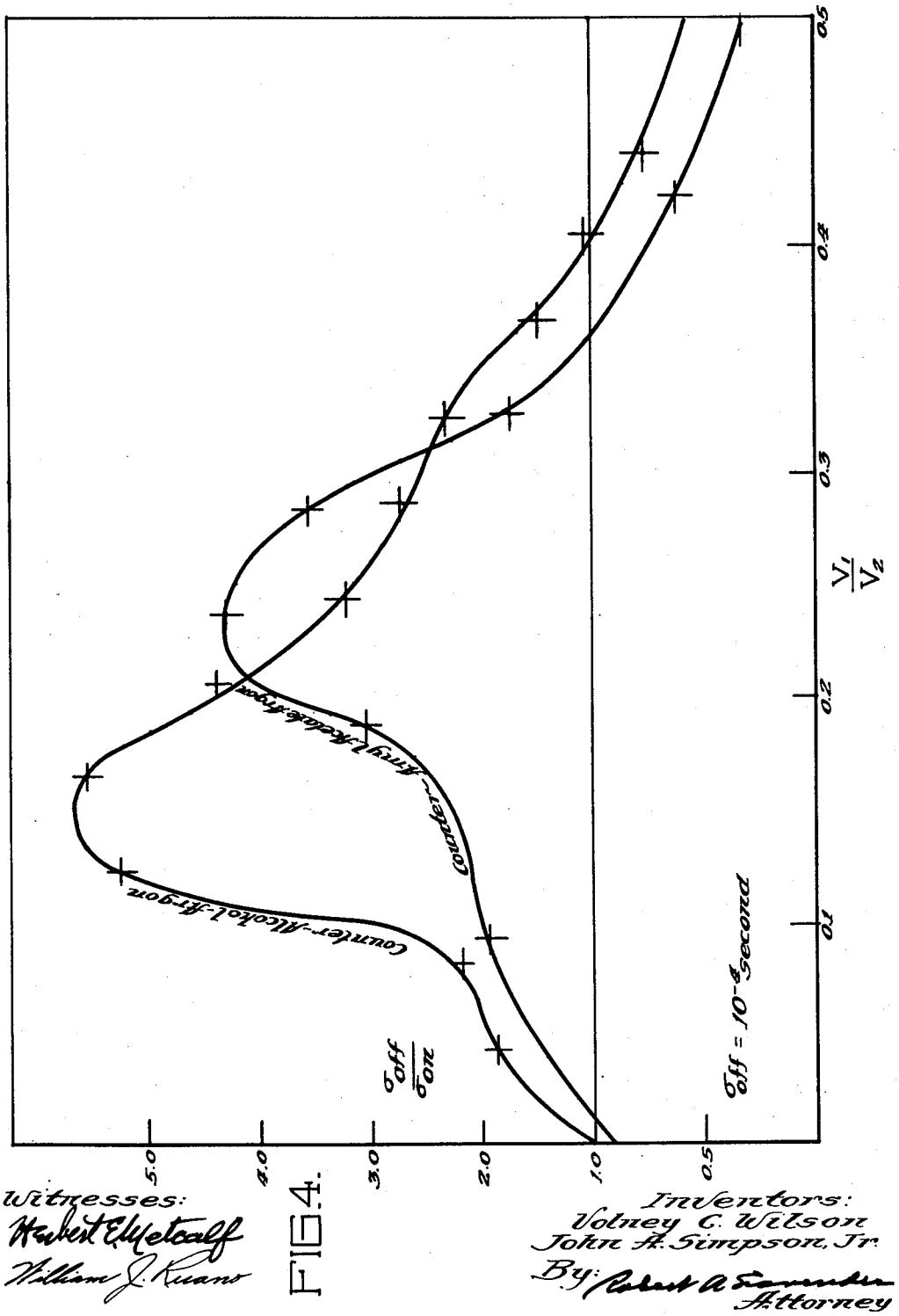


FIG. 4.

Witnesses:
Herbert E. Metcalf
William J. Ruano

Inventors:
Volney C. Wilson
John A. Simpson, Jr.
By: Robert A. Somerville
Attorney

Patented Mar. 31, 1953 2,633,540

UNITED STATES PATENT OFFICE

2,633,540

ELECTRICAL APPARATUS AND METHOD

Volney C. Wilson, Santa Fe, N. Mex., and John A. Simpson, Jr., Chicago, Ill., assignors to the United States of America as represented by the United States Atomic Energy Commission

Application April 26, 1945, Serial No. 590,425

27 Claims. (Cl. 250—83.6)

1

Our invention relates to a method and apparatus for reducing the insensitive or dead time of a gas filled electric discharge tube, such as, for example, a Geiger-Müller counter. More specifically, our invention relates to a method and electrical circuit for effecting a reduction in the natural insensitive or dead time in a tube of the Geiger-Müller type, thus making it responsive to very high counting rates.

Geiger-Müller counters and proportional counters are generally used for detecting ionizing events such as caused by the radioactive disintegration of radioactive materials. A generally used construction of a Geiger-Müller counter is one having a pair of concentric electrodes, namely a small central wire anode and a large cylindrical cathode also serving as a chamber wall that contains an ionizable medium, such as one or more permanent gases either with or without an organic vapor. In a counter having an ionizable medium including an organic vapor, the dead time or insensitive time is of the order of 10^{-4} second. This dead time occurs between the time when the initial ionization is produced and the time at which the field intensity in the region of the anode has recovered sufficiently to detect another ionizing event. A dead time of this order of magnitude is a serious limitation in obtaining accurate data at high counting rates, such as in the case of analyzing the radioactive decay process of materials of short half-life. As a result of an ionizing event, a positive ion space charge or ion sheath forms about the circular wire shaped anode and moves radially outwardly as a cloud to the cylindrical cathode where it is finally collected. The above mentioned limitation of the dead time is considered to exist because of the finite mobility of this positive ion cloud in its transit towards the cathode, which varies in accordance with the kind of gaseous medium and electric fields used.

An object of our invention is to provide a method and apparatus for decreasing the natural insensitive or dead time of a radiation counter tube, such as, for example, a Geiger-Müller tube, to values well below the natural limit of about 10^{-4} second, more specifically, to as low as 10^{-5} second or even lower, thus making the radiation counting tube at least about ten times as fast as presently known Geiger-Müller tubes.

A more specific object of our invention is to provide a method and an electrical system for accelerating the removal of the positive ion cloud formed in electric discharge tubes, such as, for example, radiation counter tubes, thereby considerably decreasing the insensitive or dead time of such tubes.

2

In its broader aspects, our invention involves the principle of employing an electric field reversing circuit for speeding up the collection of the positive ion cloud, thus making the radiation counter tube faster. In other words, instead of allowing the positive ion sheath which forms around the center wire to move outwardly, the potentials on the center wire and outer cylinder or cathode of the counter are reversed so that positive ions may be rapidly collected on the center wire instead of on the outer cylinder, inasmuch as the high field at the center wire accelerates the ions towards the center wire and allows them to be collected in a very short time, namely, in about 10^{-5} second or less. Immediately following collection of the ions by the center wire, normal operating potentials are restored in the counter to place it in condition to register the next ionizing event. In this manner of operation the outer cylinder serves only as a field forming conductor.

Other objects and advantages will become more apparent from the following specification taken with the drawings wherein:

Fig. 1 is a schematic circuit diagram showing, in block diagram form, the general components of a Geiger-Müller counter circuit embodying the teachings of our invention, together with certain voltage pulse characteristics;

Fig. 2 is a schematic circuit diagram of a detailed Geiger-Müller counter circuit, illustrated generally in Fig. 1, together with the pulse forms to be found at the various tubes;

Fig. 3 is a graph showing instantaneous values of the voltage pulses on the Geiger-Müller tube plotted against time for two different circuit conditions; and

Fig. 4 is a graph showing the factor of reduction of insensitive time

$$\frac{\sigma \text{ off}}{\sigma \text{ on}}$$

plotted against the ratio of the reversing to the operating voltage

$$\left(\frac{V_1}{V_2}\right)$$

for two counters having different gaseous compositions.

The following is a detailed theoretical description of the operation of a Geiger-Müller counter and of the principles involved in our invention.

A Geiger-Müller counter tube is an electronic

tube, or more precisely, an ion tube. Physically, it is a concentric electrode system in a vacuum-tight envelope containing a gas or mixture of gases. As illustrated schematically in Fig. 1, the anode **2** is usually a wire shaped central electrode and has a diameter generally less than 10^{-2} centimeter; the concentric cylindrical cathode **3** forming the chamber wall is very large relative to the anode. The field intensity is, therefore, inversely proportional to the radial distance from the anode **2** with very high potential gradients existing in the vicinity of the center-wire or anode **2**, and a very small gradient existing near the cylinder or cathode **3**. The gases are chosen for use in such a tube primarily for their ability to produce ions when a beta particle (B), alpha particle (α), gamma-ray (γ), or photon passes through the volume defined by cathode or cylinder **3**. There are, however, a great number of modifying conditions as will appear hereinafter which restricts severely the kinds of gases which may be used.

When an ionizing event takes place in the counter volume, the electrons produced are accelerated toward the region of the positive center-wire where, due to their relatively high energy, they produce the so-called "Townsend avalanche." In the immediate vicinity of the center-wire, the discharge spreads laterally very rapidly, the time being in the order of 10^{-7} second. The mechanism of this lateral discharge is still uncertain, but it is most probably due to photons being absorbed by gas molecules polarized in the high field.

The electrons are collected on the center wire in about 10^{-6} second. As the electrons are collected on the center wire, a uniform sheath of positive ions is left in the immediate vicinity of the center wire because of the very low mobility of these ions compared with the mobility of electrons. The positive ion sheath immediately begins to move radially outward as a cloud toward the cylindrical cathode **3** where it is collected. However, before the positive ion sheath has left the immediate vicinity of the center wire, the field existing between the positive ion sheath and center wire is reduced to such an extent that if another ionizing event should occur no avalanche would be formed. However, after the positive ion cloud has moved toward the cylindrical cathode of the order of ½ to ⅔ of the total radial distance, the field will be restored to a value that is above the critical value necessary to sustain an avalanche produced by a subsequent ionizing event. The insensitive or dead time, therefore, is the period of the time required for the positive ion sheath to move from the immediate vicinity of the center wire to a position such that the field intensity between the sheath and center-wire is high enough to support an avalanche. The insensitive time, therefore, is dependent upon the speed or mobility of the positive ions.

There are, in general, two types of Geiger-Müller counter gaseous fillings: (1) a filling of one or more inert or permanent gases, such as argon and neon, and (2) an inert and a polyatomic organic gas mixture, such as argon and alcohol vapor, or neon and amyl acetate vapor.

In a counter having a permanent gas filling, the positive ions have a high mobility, hence the time required for the positive ion sheath to move out to the critical distance is relatively short. Therefore the field intensity at the center wire returns rapidly to a value that can support a new discharge. However, an outstanding disadvantage of this type of counter is that photons and secondary electrons or photoelectrons are formed. These electrons are capable of reinitiating the discharge, thus keeping the counter in continuous discharge. In order to prevent the occurrence of a continuous discharge, it is necessary to provide an external circuit having a high RC value so as to remove the potential from the center wire following an ionizing event for an interval long enough to stop the discharge. Therefore, while the natural insensitive time of a rare gas counter is extremely low advantage cannot be taken of this low insensitive time because of subsequent production of electrons at the cathode by the arrival of the positive ion cloud. The necessity of a large RC external circuit imposes an unduly long inactive or dead time to the counter, making it unsuitable for detecting ionizing events occurring at a high rate.

Circuits have been developed (for example, H. V. Neher and W. W. Harper, Phys. Rev. 49, pp. 940–943, June 15, 1936) which quench a rare gas counter in the minimum of time. However, even though the rare gas ions have a greater mobility than the polyatomic gases, one must reduce the voltage on the counter (below the voltage at which an avalanche can be initiated) for a sufficiently long time after the initiation of a pulse so that one is sure that all the positive ions have been collected on the cathode. In practice it has been found that the minimum for this time is one or two times 10^{-4} second.

In a counter having the second type of gaseous filling, that is, for example, one containing a permanent gas and a vapor, the ions are polyatomic and, therefore, relatively heavy, hence the positive ion cloud has relatively low mobility and will take an appreciable length of time to move from the vicinity of the center wire to the vicinity of the cathode, that is, it will require a time period of the order of 10^{-4} second, which makes it unsuitable for detecting ionizing events occurring at a high rate without coincidence losses. However, one outstanding advantage of an organic vapor counter is that practically no secondary electrons or photons are formed, hence there is no necessity for delaying the restoration of the normal voltage on the center-wire. Therefore, while the positive ion mobility is lower than that of a rare gas counter, the insensitive or dead time is shorter because of the absence of additional ionization, hence avoiding the necessity of a high external RC circuit for eliminating the effects of secondary electrons and photons.

A counter containing polyatomic gas, such as alcohol, has been called in the literature a "fast" counter in contrast to the mon- or di-atomic gas counter, or rare gas counter, which is called "slow" because of the relatively long time for which the counter must be made insensitive to insure that only one count is recorded. This may be a rather unfortunate choice of terms since actually those counters containing polyatomic gases are much slower in completing the removal of ions from the initial ionizing event than the so-called "slow" counters.

Other difficulties encountered in the choice of an atmosphere for a Geiger-Müller counter are the possibilities of producing metastable atoms and negative ions. A metastable atom can produce a spurious count by causing the production

of an avalanche a considerable time after the initial avalanche has occurred. At least a trace of a foreign gas, added to a pure gas counter, is usually sufficient to remove the metastable atoms safely without producing any spurious counts. The addition of a second gas may also produce a counter having a lower starting potential because the energy from an excited level of one type of molecule is great enough to contribute to the ionization of the other type of molecule.

Negative ions have low mobilities. When they are accelerated toward the center-wire, they give up an attached electron which produces an avalanche. This process results in a spurious count. It is essential, therefore, to avoid, if possible, gases containing atoms having high electron affinities, therefore tending to form negative ions, such as BF_3, O_2, Cl I, Br, and Hg. In filling a counter evacuated with a mercury pump system without a liquid air trap, the mercury vapor pressure in the counter will be approximately 0.002 mm. Hg at room temperature. It has yet to be shown that mercury contamination has any pronounced effect on the Geiger-Müller counter action.

The voltage pulse in a "fast" counter due to an ionizing event is quite different from that in a "slow" counter. In the former case, as the RC may be very low, the pulse front is steep due to electron collection and the tail formed on the end of the voltage pulse will be rather small. However, as pointed out before, a "slow" counter must have a relatively high RC circuit to insure a faithful count. This results in a pulse which must be sharpened electronically before it can be used satisfactorily for recording unless an electronic quenching circuit is used to reduce this time.

The natural insensitive or dead time associated with each type of Geiger-Müller counter places a severe limitation on its 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 such counters. This loss of counts at high rates is expressed in an equation in which the insensitive time is δ, the true counting rate is N_t, and the observed rate is N_a: the equation is

$$N_a = N_t/(1+N_t\delta)$$

The very best conditions that can be obtained in recording data from a counter with insensitive time δ are attained when the amplifier responds to the very tiny pulses which may occur immediately after the lapse of the time interval δ 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. The natural lower limit on the insensitive time of a Geiger-Müller counter therefore limits its use in obtaining accurate data at high counting rates. The positive ion space charge in "fast" counters unduly prolongs the time that the field is below the critical value necessary for supporting a new avalanche. If a high mobility cloud could be formed, this time would be considerably reduced. Such a cloud is encountered in a permanent gas mixture of two light gases, as indicated previously, but to date no method is known for preventing secondary electrons and photons from forming in such a counter. The mobilities of all suitable polyatomic gases are of the same order of magnitude and counters should be filled to pressures of the order of 10 cm. Hg to be efficient. 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 of the counter characteristics with time, and the counter will have a very short useful life.

The ion space charge is, therefore, the controlling and limiting factor in reducing the counter insensitive time.

Another mode of operation of a Geiger-Müller counter is evidently necessary if progress is to be made in reducing the insensitive time. 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 accompanying initial drop in center-wire potential, use is not made of the subsequent cycle so far as recording the event is concerned.

In accordance with our invention, instead of allowing the positive ion sheath which forms around the center-wire to move outwardly towards the cathode, these ions are almost immediately collected on the center-wire. This can be accomplished by an electronic circuit that reverses the potentials on the center-wire and cylinder immediately after the ionizing event and maintains the potentials reversed 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 rapidly toward the center-wire, the collection time will be very short, that is less than 10^{-5} second. As soon as all ions are collected, the counter potentials are immediately restored to their normal operating values to be ready for the next ionizing event initiated by the radiations being detected. Thus the outer cylinder serves only as a field forming conductor.

By making the center-wire negative, the production of photo-electrons becomes negligible. Photo-electrons 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 cathode radius. It should be noted that tungsten, which is widely used for center-wires, has a work function of about 4.5 e.v.

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.

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 $1/r$ where r is the radial distance from the center-wire. 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, where E = the field strength and p = the pressure of the gas, 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 vaule 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 producing an oscillatory discharge.

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 will cause no difficulty because they will not materially distort the field distribution. They will not lose their electrons in a region where a new avalanche could possibly start because the field adjacent to 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 by maintaining the magnitude of the reversing voltage below a predetermined value, generally less than ⅓ of the normal operating voltage. For example, for a normal operating voltage of 800 to 900 volts a reverse potential of −150 to −180 volts has been found to be satisfactory.

In recording an ionizing event the shape and entire duration of the pulse developed across the counter in normal operation is of no particular importance, the steep pulse front which is produced in the order of 1 microsecond by the high mobility electrons arriving at the center-wire being sufficient for counting purposes. As described previously, the positive ions which remain as a result of the counter avalanche are left in the form of a sheath or space charge around the center-wire and begin to migrate to the outer electrode. In order to collect positive ions rapidly at the center-wire it is necessary to effect triggering of the circuit almost immediately upon the occurrence of the ionizing event. It is desirable, therefore, to use the first 1 or 2 volt change of counter potential which is produced by the electron collection and slight initial motion of the positive ion sheath, to detect an ionizing event and subsequently record a count. Some mechanism must be provided for transforming this first portion of the voltage pulse into a large pulse of short duration suitable for triggering an electronic circuit that is capable of reversing the potential of the center-wire with respect to the outer electrode. The total time for carrying out this potential reversing process must be short enough so that the positive ions will not have an opportunity to move any appreciable distance from the vicinity of the center-wire.

A suitable electronic method for reversing these potentials in accordance with our invention is first to amplify the small pulse front in such a way that the high frequency components of the pulse front are preserved so as to give a sharp triggering pulse. This triggering pulse can then be used to actuate an electronic circuit capable of producing a rectangular wave whose width will ultimately determine the time of positive ion collection. This newly formed wave may then be amplified and inverted so as to produce a very large pulse of the same time width capable of inverting the electrode potentials.

Fig. 1 is a schematic drawing showing in block diagram form a circuit for carrying out such method. A Geiger-Müller counter tube 1 is provided having a wire anode 2 and cylindrical cathode 3. A so-called "quenching" resistor R is connected between the cathode 3 and ground so that when an ionizing event takes place a positive pulse will appear at the cathode. This positive pulse is applied to an "amplifier and shutter" circuit. The pulse is amplified and made to actuate a "trigger pair for shutter" which produces a rectangular wave of any desired width t_1. Since it is apparent that any subsequent reversal of counter potentials also induces pulses in the amplifier, it is necessary that the amplifier be shut down from normal operation, that is, made non-responsive to incoming signals, for an interval of time long enough for the positive ion collection to take place. This is accomplished by feeding this rectangular wave of width t_1 back into the amplifier in such a way that it temporarily shuts off or blocks the amplifier. The same triggering pulse also actuates a second "trigger pair for reversing" that produces another rectangular wave whose width t_2 determines the ion collection time. This pulse is amplified in a "pulse circuit" which actually produces the inversion of potentials. Referring to the resistance network in Fig. 1; normally no current flows through resistance R_b. Hence, the potential at the point A will normally be at the same value as the positive (+) power supply high voltage V_2. The high voltage supply has a potential V_1+V_2, but a portion of this potential is negative with respect to ground, namely V_1. Since the counter tube 1 operates between ground and the point A, its center-wire 2 assumes the potential difference V_2, normally. Now when a large current flows through R_b as the result of an ionizing event for a time determined by this second rectangular wave of width t_2, the potential at point A drops, therefore, the center wire potential becomes negative with respect to the outer electrode of the counter for the period t_2, provided the amplitude of the wave form shown in Fig. 3 is greater than V_2. At the end of the interval t_2 determined by the second triggering rectangular wave, the potential at A again returns to potential V_2 with respect to ground. The counter is now ready to record another ionizing event, but the amplifier is not. The amplifier becomes sensitive after a time t_1, and then the entire system is again "sensitive."

Fig. 2 shows in detail the circuit diagram illustrated generally in Fig. 1. Referring more particularly to Fig. 2 and comparing it with Fig. 1, tubes T_1 T_2, and T_3 comprise the "amplifier and shutter," tubes T_1 and T_2 being amplifiers and T_3 being an amplifier and shutter; tubes T_4 and T_5 comprise the "trigger pair for shutter" producing the shutter pulse of duration t_1; tubes T_6 and T_7 comprise the "trigger pair for reversing" producing the pulse of duration t_2; and tubes T_8 and T_9 comprise the "pulse circuit." The network $L_5R_5R_{27}$ in the plate supply of tube T_9 corresponds to R_b in Fig. 1. In each of the tubes T_1 to T_8, inclusive, the electrodes represent in succession starting from the cathode as follows:

cathode, control grid, screen grid, suppressor grid and anode, the suppressor grid being omitted in tube T_9. Above each tube there is represented a graph of voltage plotted as ordinates versus time as abscissas of the voltage pulse applied to the input grid in the case of tubes T_2, T_3, T_4 and T_6 and appearing at the output of tubes T_5, T_7, T_8 and T_9. These pulses are not drawn to scale.

Assume that an alpha, beta, or gamma event produces ionization inside the counter tube 1. A number of ions are formed. The mobility of the electrons is about 10^3 times that of the positive ions formed. The electrons are accelerated toward the center wire where the field is very intense. In the vicinity of the center-wire they acquire sufficient energy to produce additional ionization resulting in the formation of positive ions and more electrons. The increase is exponential and a large number of electrons arrive at the center wire leaving a sheath of positive ions in the vicinity of the center-wire. As the electrons arrive at the center-wire, the discharge spreads laterally and around the wire in both directions uniformly within about 10^{-7} second. This results in the formation of a rather uniform positive ion sheath around the center-wire, which reduces the field intensity between the center-wire and the cathode to such an extent that if another ionizing event were to occur at that instant no avalanche would take place. The arrival of the electrons at the center-wire results in the beginning of the first portion of the normal Geiger counter pulse. If the counter were allowed to operate in the normal fashion, it would produce a pulse that would have the shape of the total pulse V_a shown in dotted lines associated with the voltage pulse V_b. However, it is only the first portion V_b or (first few volts change) of this pulse that is required to change the potential of the grid of the non-conducting tube T_1 so that it may become momentarily conducting so as to produce a sharp negative pulse V_2 on the control grid of the normally conducting tube T_2. It should be noted that the bias potential of tube T_1 is adjusted so that only positive pulses are amplified. The tube T_2 is operated well up in its characteristic curve and therefore will produce a highly amplified positive pulse V_3 at the grid of the normally non-conducting tube T_3. By utilizing inductances and differentiating networks such as L_2 and C_3R_7, it is possible to make the pulse V_3 extremely sharp. Tube T_3 serves two purposes first, it inverts the signal pulse producing a negative pulse V_4 at the grid of the normally conducting tube T_4, and second, tube T_3 has its suppressor grid adjusted so that this grid may make the tube inoperative when the large negative rectangular wave of time or width t_1 appears thereon through condenser C_4. Such a rectangular wave of width t_1 is produced by the biased trigger pair circuit comprising normally conducting tube T_4 and normally non-conducting tube T_5, as follows.

As a result of voltage pulse V_4 the control grid of tube T_4 becomes more negative causing the plate voltage of tube T_4 to rise. The grid voltage of tube T_5 therefore becomes more positive causing a drop in plate voltage thereof which is fed back to the control grid of tube T_4 making it even more negative and causing the plate voltage of tube T_4 and grid voltage of tube T_5 to rise further. Hence, the cycle repeats over and over again until finally tube T_4 becomes non-conducting and tube T_5 becomes conducting resulting in the first vertical portion and the beginning of the horizontal portion of the rectangular wave. This new condition is an unstable one because the charge on condensers C_5 and C_6 leaks off through resistor R_{13} and the charge on condenser C_7 leaks off through resistor R_{16}. Hence, at the end of a time period t_1 (determined by the various parameters and value of variable resistance R_{13}), tube T_4 is restored to its conducting condition, and tube T_5 to its non-conducting condition thus giving the second vertical portion of the rectangular wave. The rectangular wave is fed to the suppressor grid of tube T_3 making tube T_3 non-conducting, hence blocking off the amplifier against further translation of pulses. Tube T_3 thus acts as a shutter for the amplifier so that after an ionizing event takes place, the amplifier will not pass a subsequent pulse onto tube T_4 for a time t_1 which is the width of the rectangular wave produced by the trigger tubes T_4 and T_5. This will insure that any disturbances occurring during this time interval on the grid of tube T_1 will not be counted or trigger the reversing circuit. Simultaneously the rectangular wave is impressed on a scaling and recording circuit (not shown) which records the ionizing events.

Tubes T_6 and T_7 constitute a second trigger pair similar to tubes T_4 and T_5, that is, tube T_6 is normally conducting and tube T_7 is normally non-conducting. Tubes T_6 and T_7 are triggered by the negative portion of voltage pulse V_6 produced on the control grid of tube T_6 by differentiating pulse V_5 by circuit R_{18} C_9. Trigger pair tubes T_6 and T_7 also produce a rectangular wave V_7 on the plate of tube T_7 of duration t_2. Period t_2 may be adjusted to the desired collection time for the positive ions by varying resistance R_{18}, that is, by increasing R_{13}, t_2 becomes longer. This pulse is inverted and amplified by normally conducting tube T_8. The pulse V_8 so formed at the plate of tube T_8 then appears on the control grid of tube T_9. Tube T_9 is biased so that it is normally non-conducting and requires a large positive pulse on its grid to make it highly conducting. The large positive pulse V_8 results in the production of a much larger negative pulse V_9 at the output of tube T_9, that is, approximately equal to the potential V_1+V_2, thus it brings the plate of tube T_9 to almost cathode potential. But this drop in potential caused by current flow through circuit R_{27}—R_8—L_8 is greater than the potential existing between the center electrode 2 and the cathode 3 of the counter. Therefore, the counter potentials are inverted by this pulse for a time t_2 to a magnitude of approximately $-V_1$ volts. The pulse V_9, which is illustrated foreshortened, now makes it more apparent why the amplifier must be made inoperative for an interval of time t_1. It will be noted that the counter 1 and resistance R form an RC network with a very small time constant. This differentiates the pulse V_9 at the control grid of the tube T_1, but differentiating of pulse V_9 means that both a negative and positive sharp pulse V_c appears at the control grid of tube T_1. Tube T_1 is not sensitive to a negative pulse, but is sensitive to a positive pulse which is blocked from translation by the negatively biased shutter tube T_3 since the amplifier is shut down for a time t_1 which is greater than the time t_2. Theoretically satisfactory operation may be obtained by making $t_1=t_2$, that is, by using the rectangular wave form t_1 instead of t_2 for reversing. Practically, however, there will always be a tendency for voltage pulses to appear at tube T_1, under this critical operating

condition, therefore, ideal operation is not obtained.

There would be no advantage in this circuit if the tail portion of pulse V_9 were so great that the counter did not actually return to its normal operating condition almost immediately after the time t_2 had elapsed. The removal of this tail is accomplished by a circuit L_sR_s which dissipates the electromagnetic energy in the plate circuit upon the return of tube T_9 to normal cut-off conditions. The tail is removed by the correct choice of resistance R_s and inductance L_s. Values other than the correct values for R_s and L_s produce long characteristic tails which are undesirable.

The following table illustrates a set of operable values for the various circuit elements shown in Fig. 2, it being indicated that other values may also be chosen to give satisfactory operation:

C_1=0.1 mfd.	R_8=25,000 ohms
C_2=50 fd.	R_9=2500 ohms
C_3=20 fd.	R_{10}=25,000 ohms
C_4=0.02 mfd.	R_{11}=75,000 ohms
C_5=20 fd.	R_{12}=25,000 ohms
C_6=100 fd.	R_{13}=2 meg.
C_7=0.02 mfd.	R_{14}=10,000 ohms
C_8=10 mfd.	R_{15}=4,000 ohms
C_9=10 fd.	R_{16}=50,000 ohms
C_{10}=0.1 mfd.	R_{17}=6,000 ohms
C_{11}=100 fd.	R_{18}=1 meg.
C_{12}=.02 mfd.	R_{19}=2,000 ohms
C_{13}=500 fd.	R_{20}=50,000 ohms
C_{14}=0.001 mfd.	R_{21}=6,000 ohms
C_{15}=4 mfd.	R_{22}=0.1 meg.
L_1=1.2 mh.	R_{23}=500 ohms
L_2=0.67 mh.	R_{24}=0.1 meg.
L_3=1.2 mh.	R_{25}=15,000 ohms
L_4=80 mh.	R_{26}=50,000 ohms
R_1=3500 ohms	R_{27}=4,000 ohms
R_2=500 ohms	R_{28}=500 ohms
R_3=25,000 ohms	R_{29}=2500 ohms
R_4=25,000 ohms	R=75,000 ohms
R_5=2500 ohms	R_s=approx. 550 ohms
R_6=25,000 ohms	L_s=15 mh.
R_7=0.1 meg.	T_1 to T_8 incl.=6AC7
	T_9=type 807

The requirements for the design of the above described electronic circuit to produce the random reversals at a very high average rate with precision are stringent and may be summarized as follows:

1. The input to the amplifying device must be responsive to the first few volts drop of the steep pulse front and must be insensitive to the process of reversing the field.

2. The circuit must have extremely low RC time constant throughout, 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 collected.

4. No residual voltage "tails" more than three or four volts can be tolerated after the collection time is over otherwise 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.

Fig. 3 shows similar but enlarged curves representing the voltage pulses appearing on the plate of tube T_9. The pulse V_{9A} is obtained on the plate of tube T_9 and on the anode wire 2 in the event that the circuit L_sR_s were omitted entirely. It will be noted that a long tail of the order of magnitude of 200 volts in height will be formed causing an unusual delay in the restoration of the plate voltage to its normal value V_2. The potential at the counter cathode is indicated by V_{9b}. On the other hand by using R_s and L_s in the circuit and by choosing correct values therefore, a voltage pulse V_{9c} appears on the anode wire 2 and a voltage pulse V_{9d} appears at the cathode 3. It will be seen that practically no tail appears on pulse V_{9c} thus showing that the stabilizing circuit (or so-called LRC including R_s and L_s or its equivalent is almost indispensable for proper operation of the reversing circuit.

Fig. 4 is a graph in which the ordinate

$$\frac{\sigma \text{ off}}{\sigma \text{ on}}$$

represents the ratio of insensitive time with the reversing circuit inoperative (σ off) to the insensitive time with the reversing circuit operative (σ on). The abscissa

$$\frac{V_1}{V_2}$$

is the ratio of the reversing voltage (V_1) to operating voltage (V_2). Two curves are shown—one representing a Geiger-Müller counter tube having an alcohol-argon mixture and the other curve showing a similar counter tube having an amyl acetate-argon composition. It will be noted that without a reversing circuit, that is, when the ratio

$$\frac{\sigma \text{ off}}{\sigma \text{ on}}=1$$

the resolving time is about 10^{-4} second. On the other hand, when the reversing circuit is used the optimum value of (σ on) may be of the order of 2×10^{-5} second for the alcohol-argon counter. This optimum value is indicated by the peaks of the curve, since increasing values of the ordinate represent decreasing values of the insensitive time. Thus for a counter having an alcohol-argon mixture, it is seen that for obtaining an optimum insensitive time, namely one in which

$$\frac{\sigma \text{ off}}{\sigma \text{ on}}=\text{about } 5$$

it is necessary that the ratio

$$\frac{V_1}{V_2}$$

be about .15. Stated differently, in order to obtain optimum (minimum) values of insensitive time, the ratio of

$$\frac{V_1}{V_2}$$

should be less than .3 for the two counters illustrated. It should also be noted that the proper value of reversing potentials to be used for obtaining the optimum results, that is, for obtaining the greatest decrease in insensitive time is dependent upon many variables such as, for example, the particular gaseous mixture used, the time of collection (that is, the width of the reversing pulse and the shutter pulse width), etc. Insensitive times of a value of 2×10^{-5} second and lower have been readily obtainable by the above described reversing scheme. Operation of the system indicates that much lower values, of the order of 10^{-6} or lower may be obtained

with better operating conditions. In plotting the values shown in Fig. 4, the shutter pulse t_1 was set at 1.5×10^{-5} second, and with this adjustment the new insensitive time is about 2×10^{-5} second. The time t_2 was varied to 2.5×10^{-6} second.

It will be seen therefore that we have provided an efficient method and electronic circuit for momentarily effecting reversal of the potentials of a Geiger-Müller tube so as to reduce the insensitive time thereof, that is, make it at least 10 times as fast in response as the type of circuit used in well-known Geiger-Müller circuits, thus making such tubes suitable for counting pulses occurring at a very rapid rate. While our reversing scheme by way of illustration has been described as useful for reducing the insensitive time of a Geiger-Müller tube, it should be noted that it is likewise useful for reduction of insensitive time for other electrical discharge tubes.

It should also be noted that while a specific circuit has been described in detail to illustrate the principles of our invention, other equivalent circuits for accomplishing the same results may be readily suggested to those skilled in the art after having had the benefit of the teachings of the present specification which circuits, however, come within the general spirit of our invention. For this reason, our invention should not be restricted except as set forth in the following claims.

We claim:

1. The method of operating a gas-filled Geiger-Müller counter tube comprising applying operating potentials to the electrodes thereof, reversing the polarity of said electrodes in response to initiation of ionization in said tube as the result of entry of a radiation impulse therein, and restoring said potentials to their initial operating value within a period of less than 10^{-4} second.

2. The method of operating gas-filled Geiger Müller counter tube having a pair of electrodes, one of said electrodes being an anode and the other a cathode, comprising applying operating potentials to said tube, a positive potential being applied to the anode and a negative potential being applied to the cathode, reversing said potentials as the result of initiation of an ionizing event, thereby rapidly collecting positive ions on said anode electrode, and rapidly restoring said potentials to their initial operating value after substantial collection of said positive ions.

3. The method of operating a gas-filled Geiger-Müller counter tube having a central electrode serving as an anode and a surrounding cylindrical cathode, comprising applying operating potentials to said tube, reversing said potentials as the result of initiation of an ionizing event, thereby rapidly collecting positive ions on said central electrode, and rapidly restoring said potentials to their initial operating value within a period of the order of 10^{-5} second following said reversal.

4. The method of operating a gas-filled Geiger-Müller tube having a pair of spaced apart electrodes, one of said electrodes being an anode and the other a cathode, comprising developing positive ion sheath in the vicinity of said anode as the result of an ionizing event, momentarily applying a negative potential to said anode thereby collecting said positive ion sheath by said anode, and conditioning said tube for reionization within a time between 10^{-4} and 10^{-5} second.

5. The method of operating a Geiger-Müller counter system including a gas-filled Geiger-Müller counter tube and an amplifying tube for amplifying the effects of ionizing events in said counter tube comprising applying operating potentials to the electrodes of said counter tube to develop a flow of electrons in response to an ionizing event, developing a pulse of predetermined time duration in response to said flow of electrons, and applying said pulse to said amplifier to block said amplifier while simultaneously employing said pulse to effect reversal of potentials on said counter tube electrodes to effect rapid collection of positive ions formed therein, and thereafter rapidly restoring said reversed potentials to their initial operating value so as to condition the counter tube for a subsequent ionizing event.

6. The method of operating a Geiger-Müller counter system including a gas-filled Geiger-Müller counter tube and an amplifying tube for amplifying the effects of ionizing events in said counter tube comprising applying operating potentials to the electrodes of said counter tube to develop a flow of electrons in response to an ionizing event, developing a pulse of predetermined time duration from said flow of electrons, and applying said pulse to said amplifier to block said amplifier, substantially simultaneously developing a second pulse of shorter duration than said first pulse and utilizing said second pulse to effect reversal of potentials on said counter tube to effect rapid collection of positive ions, and thereafter rapidly restoring said reversed potentials to their initial operating value.

7. The method of operating a Geiger-Müller counter system including a gas-filled Geiger Müller counter tube and an amplifying tube for amplifying the effects of ionizing events in said counter tube comprising applying operating potentials to the electrodes of said counter tube to develop a flow of electrons in response to an ionizing event, developing a first voltage pulse of predetermined time duration in response to said flow of electrons, and applying said pulse to said amplifier to block said amplifier, substantially simultaneously developing a second voltage pulse of shorter duration than said first pulse and utilizing said second pulse to effect reversal of potentials on said counter tube to effect rapid collection of positive ions, and thereafter rapidly restoring said reversed potentials to their initial operating value, said voltage pulses being of substantially rectangular wave form and having time durations of less than 10^{-4} second.

8. The method of operating a Geiger-Müller counting system including a gas-filled dual electrode Geiger-Müller tube, an amplifier circuit including an amplifying shutter tube and a normally non-conducting pulse amplifier tube, comprising applying operating potentials to the electrodes of said counter tube to develop a flow of electrons in response to an ionizing event, developing a first voltage pulse in response to said flow of electrons of time duration less than the transit time of the positive ion space charge between the electrodes of said counter tube, applying said pulse to said amplifying and shutter tube to block it against response to subsequent incoming signals, substantially simultaneously developing a second voltage pulse of shorter time duration than said first pulse and utilizing said second pulse to make said pulse amplifier tube conducting and thereby effect reversal of potentials on said counter electrodes

for a period equal to the duration of said second pulse.

9. The method of operating a gas-filled Geiger-Müller tube having a central anode and a surrounding cylindrical cathode comprising alternately depressing the anode potential to a value less than the cathode potential for periods of the order of 10^{-5} second in response to ionizing events to cause collection of the positive ion space charge by said central anode, and thereafter restoring said anode potential to its initial value after each reversal so as to condition the tube for a subsequent ionizing event.

10. In combination with a gas-filled self-quenching Geiger-Müller tube having a central wire anode and a surrounding cylindrical cathode, electric means responsive to the initiation of ionizing events to depress the anode potential to a value less than the cathode potential for periods of time substantially less than the inter-electrode transit period of positive ions formed therein.

11. In combination with a gas-filled Geiger-Müller tube comprising a center wire serving as an anode and a surrounding concentric cylindrical cathode, means for applying operating potentials to said electrodes, means responsive to the initial portion of an ionization pulse front to reverse said operating potentials for a period of the order of 10^{-5} second to effect rapid collection of ions comprising the positive ion sheath formed as the result of said ionization pulse.

12. A radiation counting system comprising a gas-filled Geiger-Müller counter tube having an anode and cathode, means for applying operating potentials thereto, amplifying means responsive to the first few volts change of a pulse front resulting from an ionizing event for translating an amplified pulse for recording purposes, and means also responsive to said pulse front for effecting reversal of said operating potentials on said counter for a period of less than 10^{-4} second to effect rapid collection of ions comprising the positive ion sheath developed in the counter as the result of said ionizing event.

13. A radiation counting system comprising a gas-filled Geiger-Müller counter tube having an anode and cathode, means for applying operating potentials to said electrodes, amplifying means responsive to a small initial portion of an ionizing event pulse for translating a voltage pulse for recording purposes, means to develop a rectangular voltage wave having a time duration substantially less than the inter-electrode transit time for positive ions developed in said counter tube as the result of an ionizing event, means for applying said rectangular voltage wave to said amplifying means to block it, and means controlled by said rectangular wave for substantially simultaneously reversing said counter operating potentials for a period less than the duration of said rectangular wave for effecting rapid collection of positive ions in said counter tube to reduce the insensitive time thereof.

14. A radiation counting system comprising a gas-filled Geiger-Müller counter tube having an anode and cathode, means for applying operating potentials to said electrodes, amplifying means responsive to a small initial portion of an ionizing event pulse for translating a voltage pulse for recording purposes, a trigger-pair of electric discharge tubes interconnected so that one tube is conducting while the other is non-conducting to develop a rectangular voltage wave having a time duration substantially less than the inter-electrode transit time for positive ions developed in said counter tube as the result of an ionizing event, means for applying said rectangular wave to said amplifying means for blocking thereof and means controlled by said rectangular wave for substantially simultaneously reversing said counter operating potentials for a period less than the duration of said rectangular wave for effecting rapid collection of positive ions in said counter tube to reduce the insensitive time thereof.

15. A radiation counting system comprising a gas-filled Geiger-Müller counter tube having an anode and cathode, means for applying operating potentials to said electrodes, amplifying means responsive to a small initial portion of an ionizing event pulse for translating a voltage pulse for recording purposes, a trigger-pair of electric discharge tubes interconnected so that one tube is conducting while the other is non-conducting to develop a rectangular voltage wave having a time duration substantially less than the inter-electrode transit time for positive ions developed in said counter tube as the result of an ionizing event, a second trigger pair of electric discharge tubes responsive to said rectangular wave to develop substantially simultaneously a second rectangular voltage wave having a time duration less than that of said first rectangular wave to effect reversal of said counter operating voltages for a period of time equal to the width of said second rectangular wave to effect speedy collection of positive ions and thereby reduce the counter insensitive time.

16. A radiation counting system comprising a gas-filled Geiger-Müller counter tube having an anode and cathode, means for applying operating potentials to said electrodes, amplifying means responsive to a small initial portion of an ionizing event pulse for translating a voltage pulse for recording purposes, means to develop a rectangular voltage wave having a time duration substantially less than the inter-electrode transit time for positive ions developed in said counter tube as the result of an ionizing event, means for applying said rectangular voltage wave to said amplifying means to block it, and means controlled by said rectangular voltage wave to generate a second rectangular voltage wave of identical starting time but of shorter duration than the first rectangular voltage wave, and means controlled by said second rectangular voltage wave for reversing said counter operating potentials for a period equal to the duration of said second rectangular wave for effecting rapid collection of positive ions in said counter tube to reduce the insensitive time thereof, said last named means including a normally non-conducting pulse amplifying tube having an anode connected with said counter anode, said pulse amplifying tube being controlled by said second rectangular voltage wave so as to become conducting and effect depression of its anode potential below the counter tube cathode potential.

17. A radiation counting system comprising a gas-filled Geiger-Müller counter tube having an anode and cathode, potential means for applying operating potentials thereto, amplifying means responsive to the first few volts change of a voltage pulse front resulting from an ionizing event for translating an amplified voltage pulse for recording purposes, and means also responsive to said pulse front for effecting reversal of said operating potentials on said counter for a period of less than 10^{-4} second to effect rapid collection of the positive ion sheath developed in the counter as the result of said ionizing event,

said last named means including an inductance and resistance network connected in series with said potential means and said anode and having such values as to substantially eliminate pulse tail formation at the anode.

18. A radiation counting system comprising a gas-filled Geiger-üller counter tube having an anode and cathode, potential means for applying operating potentials to said electrodes, amplifying means responsive to a small initial portion of an ionizing event pulse for translating a voltage pulse for recording purposes, means to develop a rectangular voltage wave having a time duration substantially less than the inter-electrode transit time for positive ions developed in said counter tube as the result of an ionizing event, means for applying said rectangular voltage wave to said amplifying means to block it, and means controlled by said rectangular voltage wave for substantially simultaneously reversing said counter operating potentials for a period less than the duration of said rectangular wave for effecting rapid collection of positive ions in said counter tube to reduce the insensitive time thereof, said last named means including an inductance and resistance network connected in series with said potential means and said anode and having such values as to substantially eliminate pulse tail formation at the anode.

19. A radiation counting system comprising a gas-filled Geiger-Müller counter tube having an anode and cathode, means for applying operating potentials to said electrodes, amplifying means responsive to a small initial portion of an ionizing event pulse for translating a voltage pulse for recording purposes, pulse-forming means to develop a rectangular voltage wave having a time duration substantially less than the inter-electrode transit time for positive ions developed in said counter tube as the result of an ionizing event, means for applying said rectangular voltage wave to said amplifying potential-reversing means to block it, and means controlled by said rectangular voltage wave for substantially simultaneously reversing said counter operating potentials for a period less than the duration of said rectangular wave for effecting rapid collection of positive ions in said counter tube to reduce the insensitive time thereof, each of said pulse-forming and potential-reversing means comprising a trigger pair of electric discharge tubes interconnected so as to become alternately conducting, the first tube of said trigger pairs being normally conducting.

20. A radiation counting system comprising a gas-filled Geiger-Müller counter tube having an anode and cathode, means for applying operating potentials to said electrodes, amplifying means responsive to a small initial portion of an ionizing event pulse for translating a voltage pulse for recording purposes, a trigger-pair of electric discharge tubes interconnected so that one tube is conducting while the other is non-conducting to develop a rectangular voltage wave having a time duration substantially less than the inter-electrode transit time for positive ions developed in said counter tube as the result of an ionizing event, said amplifying means including a normally non-conducting shutter tube becoming conducting in response to said initial portion of said ionizing event and including a suppressor grid, means for applying said rectangular voltage wave to said suppressor grid to make the shutter tube non-conductive and block said amplifying means so as not to translate further incoming pulses for the time duration of said rectangular voltage wave, and means controlled by said rectangular voltage wave for substantially simultaneously reversing said counter operating potentials for a period less than the duration of said rectangular voltage wave for effecting rapid collection of positive ions in said counter tube to reduce the insensitive time thereof.

21. The method of operating a gas-filled Geiger-Müller tube including an anode and cathode that comprises applying operating potentials to said anode and cathode, then depressing the anode potential to a value that is negative with respect to the cathode in response to an ionizing event so as to effect rapid collection of positive ions, and finally restoring the potentials to their original operating values.

22. The method of operating a gas-filled Geiger-Müller tube including an anode and cathode that comprises applying operating potentials to said anode and cathode, then depressing the anode potential to a value that is negative with respect to the cathode and less than one-third of the anode operating potential in response to an ionizing event so as to effect rapid collection of positive ions, and finally restoring the potentials to their original operating values within a period less than 10^{-4} second from the initiation of said ionizing event.

23. In the operation of a radiation-responsive tube used for detecting ionizing events occurring at a very rapid rate, a method of dispelling an ion sheath surrounding an electrode having a potential of the same polarity, comprising rapidly reversing the potential of said electrode in response to the initial portion of an ionization discharge, thereby rapidly collecting positive ions, and thereafter immediately restoring said potentials to their initial value.

24. In the operation of a radiation-responsive tube, a method of dispelling an ion sheath surrounding an electrode having a potential of the same polarity, comprising the steps of rapidly reversing the polarity of the potential of said electrode in response to the initial portion of an ionizing event, thereby rapidly collecting positive ions, and restoring said potential to its initial value within a period less than 10^{-4} second.

25. Apparatus for reversing the polarity of a voltage applied to an electric element having two terminals comprising, in combination, a source of direct voltage having a positive terminal, a negative terminal, and a tap having a potential intermediate between the potentials of said terminals, an electrical impedance connected to said positive terminal, an electron discharge tube having a cathode connected to said negative terminal, an anode connected to said electrical impedance, and a control electrode, means for connecting the junction point of said anode and said electrical impedance to one terminal of said electrical element and means for connecting said tap on said voltage source to the other terminal of said electrical element, and means for impressing upon said control electrode a voltage adapted to change the conduction between said cathode and said anode so that in the absence of said voltage on said control electrode, the anode is positive with respect to the tap on the source of voltage, but upon the appearance of the voltage upon the control electrode, the anode is negative with respect to the tap upon the source of voltage.

26. Apparatus of the class described compris-

ing, in combination, a gas-filled discharge tube having an anode and a cathode, an amplifier adapted to amplify voltage pulses, means for converting the commencement of a discharge in said discharge tube into a voltage pulse adapted to actuate said amplifier, pulse-forming means adapted to produce a voltage pulse of fixed duration shorter than the deionization time of said discharge tube, means for causing the last said pulse to deactivate said amplifier during the duration thereof, and means responsive to the commencement of a discharge in said discharge tube for substantially simultaneously reversing the polarity of the potential applied to said discharge tube so that collection of ions therein is accelerated.

27. Radioactivity measurement apparatus comprising, in combination, a Geiger-Müller tube having an anode and a cathode, a direct voltage source having a positive terminal, a negative terminal and a tap intermediate between said terminals, an electron discharge tube having a cathode connected to said negative terminal and having an anode connected to said positive terminal through an electrical impedance, the anode of said Geiger-Müller tube being connected to the junction point between said anode of the electron discharge device and said electrical impedance, and the cathode of said Geiger-Müller tube being connected to said tap on the voltage source, said electron discharge device having a control electrode adapted to change the conduction in said electron discharge device so that the polarity of the voltage appearing between the electrodes of said Geiger-Müller tube varies in response to variation of the potential of said control electrode.

VOLNEY C. WILSON.
JOHN A. SIMPSON, JR.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
2,071,759	Minorsky	Feb. 23, 1937
2,141,343	Campbell	Aug. 12, 1938
2,224,832	Pfister	Dec. 10, 1940

OTHER REFERENCES

"Reduction of the Natural Insensitive Time in G-M Counters," Simpson, Jr. (Rec'd. February 18, 1944, by the editors of the Physical Review)—Physical Rev., vol. 66, Nos. 3 and 4, August 1 and 15, 1944, pgs. 39–47. 250–83.6 Lit.

Strong-Procedures in Experimental Physics, 1942 Edition, pages 267, 268, 275–277. 250–83.6.

Reich—Theory and Applications of Electron Tubes; 1944, pages 446, 447, 128 and 129 (copy in Div. 54).

Hull—Hot Cathode Thyratrons, General Electric Review, vol. 32, No. 4, April 1929, pgs. 221, 222 (copy in Div. 54).