The Geiger-Müller Counter

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UNITED STATES DEPARTMENT OF COMMERCE • Charles Sawyer, *Secretary*
NATIONAL BUREAU OF STANDARDS • E. U. Condon, *Director*

The Geiger-Müller Counter

by **Leon F. Curtiss**

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Preface

The National Bureau of Standards receives frequent requests for information regarding the nature, construction, and use of Geiger-Müller counters. This circular has been prepared to supply this information in a brief and elementary form that still includes a description of the more important features of the basic mechanism by which these counters detect the various types of radioactive radiations. Specific examples of the various forms of counters that have been developed for particular uses are illustrated to indicate the diversity of modifications that are possible. The term "Geiger counter" often is intended to include the accessories that are necessary to obtain an indication of the response of the counter to radiation. Therefore, a discussion of some of the electronic circuits commonly used for this purpose is included. A brief bibliography of scientific papers relating to this subject offers an opportunity for those readers who wish to pursue the subject in more detail to become familiar with the literature in this field.

E. U. CONDON, *Director.*

Contents

I. Introduction

The Geiger-Müller counter, which has become one of the most important detectors of radioactive radiation in use today, has evolved from attempts to use electrical methods for the detection of alpha particles. The counting of these particles was an essential part of the experiments performed by Rutherford and his students, which led to the confirmation of the Bohr concept of the atom as consisting of a dense core having a positive charge surrounded by electrons. In these experiments alpha particles were used to probe the interior of the atom, and from the relative numbers of the particles emerging at various angles the essential features of the atomic structure were deduced. The simplest method for detecting alpha particles, and the one used almost exclusively in these experiments, was that of counting visually the minute

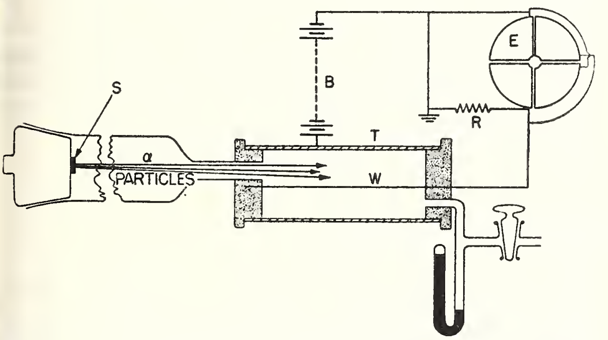

Figure 1. *Apparatus used by Rutherford and Geiger for electrical counting of alpha particles.*

S=source, W=center wire, T=metal tube, E=quadrant electrometer, B=battery, R=resistor for discharging the center wire system.

flashes of light produced when an alpha particle strikes a screen on which zinc sulphide has been deposited. These scintillations were observed through a microscope of low power requiring the concentrated attention of the observer. This method of securing data was slow and tedious, requiring a number of observers to reduce the effects of fatigue of the eye. The data secured in this way was of inferior accuracy because the total number of particles counted was usually limited to bring the time required for an experiment within a reasonable limit. It is not surprising that from time to time attempts were made to devise electrical methods for counting particles. The basis for such an electrical method is the production of ions by alpha particles as they pass through a gas. The trail of ions left by the particles constitute electric charges, which it was presumed could be collected by an electric field and detected to reveal the passage of each particle. The ionization process consists initially of removal of electrons from neutral gas atoms by the action of the electric charge on the electrons as the particle passes near or through the atoms. Therefore, this results in freeing one or more electrons from each atom ionized so that the residual atom is ionized positively. Thus both positive and negative ions are formed. Those with positive charge are heavy compared with the electrons and therefore move much

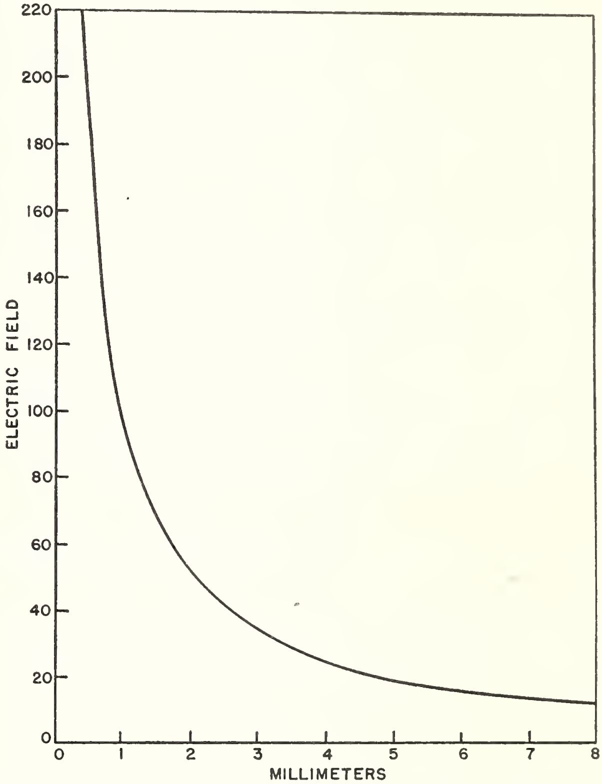

Figure 2. *Variation of the electric field with distance from the axis of the center wire.*

more slowly in the presence of an electric field. Ultimately the electrons may become attached to neutral atoms converting them into heavy negative ions. Townsend, in 1901, discovered that when the appropriate electric field is applied to an ionization chamber operated at a reduced pressure, ions formed in the chamber can be accelerated to velocities where they also will be able to ionize neutral atoms of the gas. He found that this resulted in a very sudden increase of the ionization current until it had a value many times that represented by the original ions. This phenomenon is called the Townsend avalanche in recognition of the discoverer and of the abrupt nature of the process.

This information was available to Rutherford and Geiger, who in 1908 described one of the early attempts at electrical counting of alpha particles. The device used by them is illustrated in figure 1. The counting chamber consisted of the brass tube, *T*, fitted with ebonite stoppers, which are vacuum tight. A central wire, w, is supported by these stoppers. Provision is made for evacuating the counting chamber and an attached glass tube containing the source, S, of alpha particles. The electrical connections consisted of a battery, B, of about 1,300 v and an electrometer, E, connected to the wire of the counting chamber as shown.

A ballistic throw of the electrometer needle of about 10 divisions was obtained from each alpha particle entering the counting chamber. This arrangement was so sluggish in response that only three to five particles per minute could be tolerated if serious overlapping of successive throws of the electrometer were to be avoided. The geometrical arrangement of the electrodes in this counting chamber produces an intense electric field near the center wire. Actually, for a constant potential difference between the electrodes, the field varies as $1/r$, where r is the distance from the axis of the center wire. Figure 2 is a curve showing this variation of the field for values of r from 0.5 to 8 mm. This particular disposition of electrodes provides high electric fields by use of moderate potentials. It has other advantages in connection with Geiger-Müller counters that will be pointed out later.

The counting chamber of figure 1 is not a Geiger-Müller counter, although in form it closely approximates such a device. The Geiger-Müller counter did not appear until 20 years after the development of the alpha-particle counting chamber. The chief differences in construction between the Geiger-Müller counter and these earlier devices consist in the use of a finer central wire. The gas pressures, the voltages, and the diameter of the tube are very nearly the same in both cases. The counting chamber described by Rutherford and Geiger had a tube 1.77 cm in diameter, operated at a pressure of 2 to 5 cm and at a voltage of 1,320 v. This corresponds roughly to the operating conditions for present-day counters. The reason that this counter operated as what is now known as a proportional counter instead of as a Geiger-Müller counter, apparently is that the center wire was larger than is required to provide Geiger-Müller operation at the voltage used. The wire used was 0.45 mm in diameter, which is 5 to 10 times the diameter of wires used in Geiger-Müller counters. Small variations of diameter of the center wire produce pronounced changes in the electric field, as shown by figure 2, where distances plotted on the x-axis are regarded as radii of the center wire.

II. The Geiger-Müller Counter

The brief announcement made by Geiger and Müller[1] of the tube counter revealed the extraordinary sensitivity of this device for detection of radioactive radiation. They showed that 1 mg of radium at 1 m would produce 5,500 counts per minute in a tube counter 3 cm in diameter and 17 cm long. They could detect the gamma rays from potassium with ease, something that had previously been demonstrated by the use of extremely sensitive electrometers. The tube counter was also shown to be sensitive to cosmic rays.

Although the basic picture has not been changed, a considerable amount of more definite information is now available regarding the mechanism by which the Geiger-Müller counter responds to ionizing radiation. In the course of the investigations that have led to this more complete understanding of the mode of action, a number of improvements in the design and operation have been made. Therefore, the present-day Geiger-Müller counter is superior in many ways to the original model.

One of the important features of the Geiger-Müller tube counter, not mentioned in the original article describing it, is that the tube must be at a negative potential with respect to the wire. The reason for this will appear from a description of the ionization processes in the counting operation. Another detail of the original tube counter was that the resistance between the center wire and source of potential could not be less than 10^8 to 10^9 ohms. In these first experiments a string electrometer was used to detect the pulses. The complete circuit of the counter is shown in figure 3. In this instance the 1,200 v was supplied by a battery. The gas in the tube was air at about 5 cm Hg pressure.

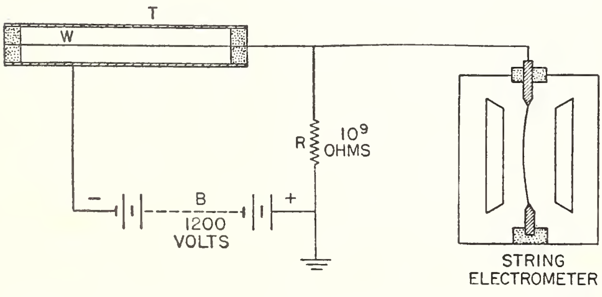

FIGURE 3. *Diagram of the counter as developed by Geiger and Müller.*

T=metal tube, W=center wire, B=battery, R=resistor.

[1] H. Geiger and W. Müller, Phys. Zs 29, 839 (1928).

1. Mode of Operation

The operation of the counter depends on the formation of Townsend avalanches within the gas of the counter tube. As little as one pair of ions is sufficient to trigger the counter. These primary ions begin to move under the influence of the electric field, the positives going to the tube and the negatives, largely electrons, moving in the direction of the center wire. Thus the electrons move into the region of the rapidly increasing electric field where they soon acquire sufficient energy to produce additional ions by collisions with neutral atoms of the gas. The positive ions move much more slowly because of their greater mass, and therefore do not produce significant amount of secondary ions. As each new generation of electrons is produced it, in turn, acquires sufficient energy to ionize the gas as it moves toward the wire. The result is great amplification of the primary ionization by the time this electrical disturbance reaches the wire. The amplification in this process is of the order of 10^9. More details of the mechanism of the action of the self-quenching counters will be given in the sections dealing with this form, which is the most common form in general use at present.

The description of the process that produces a pulse outlined above implies that a certain minimum potential is required across the counter before it will operate as a Geiger-Müller counter. This is the potential at which electron avalanches begin to form. Above this potential the size of the individual pulses will grow with the increase of voltage, but the number of pulses per second for a constant source of radiation should, on the average, remain practically constant. This condition should continue until the voltage reaches a point where the shielding effect of the positive ion sheath begins to break down and a continuous discharge across the counter can be set up. This prediction is verified in the curve shown in figure 4. In this graph the counting rate is plotted along the y-axis and the potential across the counter along the x-axis. This data is taken with a constant source of radiation and reveals the effect of the increase in potential on the operation of the counter. The value of the voltage at which counting begins is called the starting voltage. In some cases this has been defined as the extrapolated intersection of the rising curve back to the x-axis. This helps to avoid the ambiguity in the determination of the point at which counting starts. This point is actually a function, to some extent, of the sensitivity of the detecting circuit. The nearly horizontal part of this curve, called the plateau, represents the possible working range. If the source of potential for the counter is somewhat variable, it is usually advisable to select the middle of the plateau as the mean value of the voltage applied to the counter. The slope of this plateau in a good counter is not over 2 to 5 percent per hundred volts over a region of the order of 200 v. The actual slope sets the limit of the permissible fluctuation in the high voltages for a given accuracy of measurement.

The threshold voltage of the Geiger counter is defined as the voltage across the counter at which the Geiger action begins. As has been mentioned,

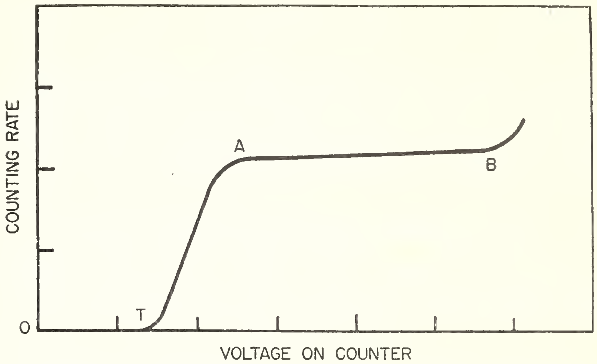

FIGURE 4. *Plateau of the Geiger-Müller Counter.*
T=starting voltage, A-B=working range.

in this region the pulses for a given voltage are uniform in height. The threshold is usually greater than the starting voltage, and the difference between it and the starting voltage depends in part on the sensitivity of the equipment used for detecting the pulses. As has been indicated, counters are operated, corresponding to some point on the plateau, at a voltage in excess of the threshold voltage. This excess is called the over-voltage. The magnitude of the pulses increases with the over-voltage.

In the Geiger region, which occurs when the potential applied across the counter, in relation to the dimensions of the center wire and tube as well as the gas pressure, are appropriately chosen, all pulses are closely of the same size for a given voltage regardless of the number of primary ions that initiated the pulse. This is a natural result of the large gas amplification obtained in the electron avalanche type of discharge. When the avalanche has reached it, the wire suffers a sudden change of potential as the result of the removal of the positive ions from the vicinity of the wire by the strong electric field in this region. This change of potential is in the direction of lowering the potential difference across the tube. The resistor connected to the center wire has a high value, so that this reduction of potential persists for a measurable time. This process results in the interruption of the electrical discharge and the termination of the counting operation. The resistor permits the charge to leak off the central wire, thus restoring the counter to its initial condition, ready to record another count. If the resistor did not have a value of the order of 10^9 ohms, a continuous discharge would tend to form in the counter tube, fed by electrons released from the walls of the tube by the impact of the positive ions. This situation is characteristic of all counters using a permanent gas for filling. These counters are also slow counters due to their long recovery time. This time is related to the value of RC, where R is the 10^9 ohm resistor, and C is the capacity of the wire system. This capacity is usually of the order of 10 $\mu\mu$f or 10^{-11} farad. Therefore, RC is equal to 0.01 sec, being the time required for the wire to fall to $1/e$ of the maximum charge in its potential. Ions formed in the counter at intervals less than 0.01 sec apart could hardly be expected to produce clearly defined separate pulses in the counter.

2. External-Quenching Circuits

Attempts have been made to convert these slow counters to relatively fast operation by use

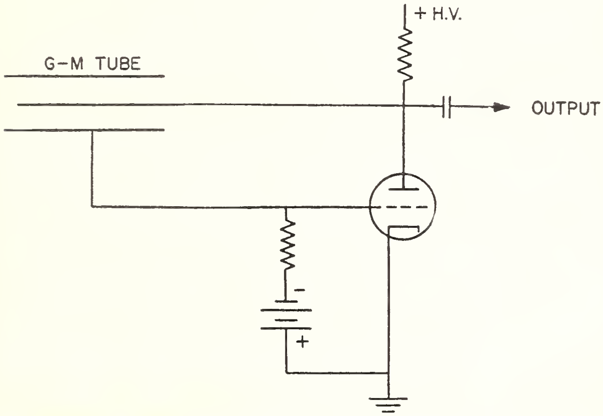

Figure 5. *Quenching circuit of Neher and Harper for rapid extinguishing of the counter discharge in permanent gas counters.*

The counter voltage is applied at +HV.

of an external electronic quenching circuit. The function of this circuit is to reduce the potential across the counter abruptly whenever an initial discharge occurs in the counter. Typical quenching circuits are shown in figures 5 and 6. These circuits are fairly effective, but they have several disadvantages. Among them are that the quenching circuit really controls the operation of the counter. Therefore, it may introduce spurious pulses if improperly adjusted. Furthermore, they usually require application of voltages to electrodes of vacuum tubes that are far in excess of the normal ratings.

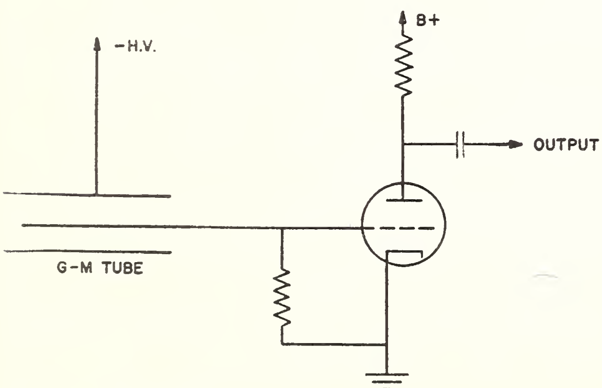

Figure 6. *The Neher-Pickering quenching circuit.*

3. Self-Quenching Counters

The next important improvement in Geiger-Müller counters consisted in adding alcohol vapor to the filling gas and choosing a gas, argon, which does not easily form heavy negative ions. This improvement was suggested by Trost.[2] The value of this type of filling gas can be more readily understood by a detailed consideration of the ionization processes by which a pulse is regis-

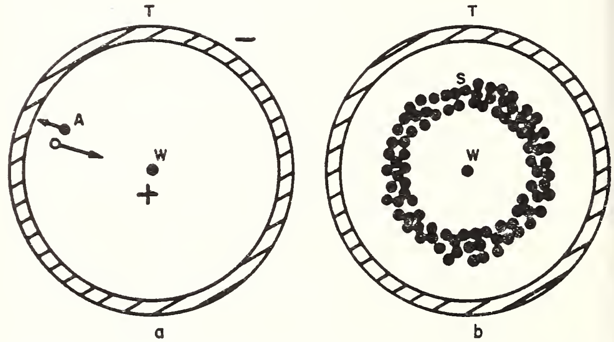

Figure 7. *Diagram showing steps in formation of an electron avalanche and the positive ion sheath.*

W=center wire, T=tube, A=initial ion pair, S=ion sheath.

tered in a tube counter. If we consider a section of the tube at right angles to the axis, it has the form shown in figure 7,a, where a newly formed pair of ions is shown at A. The arrows indicate that the negative ion or electron is moving toward the wire and the positive to the tube. The electrons proceed to form an avalanche in such a manner that the majority of the ions are produced very near the center wire. This process occurs very quickly, resulting in the collection of the electrons on the center wire. However, the positive ions that have formed a sheath about the wire move much more slowly, and most of them therefore are at some point intermediate between the wire and the tube, as shown in figure 7,b, when all of the electrons have been collected. No new electron avalanche can be formed in the space between S and the center wire, since the electric field in this region is reduced below the point at which electrons acquire sufficient energy to produce the ions. This condition will continue until the positive ion sheath has moved out to some position near the barrel of the counter tube. In a counter filled with a permanent gas the positive ions in the sheath can eject electrons from the metal wall of the tube and thus initiate additional electron avalanches which quickly form a continuous discharge. Also, it is known that the ionization is propagated throughout the length of the wire by action of the ultraviolet radiation emitted during the recombination of ions occurring in the sheath when close to the wire. This radiation can also contribute

[2] A. Trost, Zs.f.Phys. 105, 399 (1937).

to the production of a continuous discharge by releasing electrons photoelectrically from the walls of the tube.

Alcohol vapor absorbs photons in the region of energies capable of strong ionization. Molecules of alcohol vapor also have the property of absorbing energy from positive ions resulting in decomposition of the alcohol molecule, but in the formation of no light negative ions. This property reduces the liberation of electrons from the walls of the tube by positive ions. Similarly, the absorption of photons by alcohol vapor restricts the ionization by photons to a region very near the center wire. Therefore they do not release electrons at any point where an avalanche might be created as a result.

The effect, therefore, of the addition of the alcohol vapor has been to produce conditions under which the ionization process ceases abruptly when the avalanche reaches the center wire. This action is chiefly independent of the change of potential of the center wire on arrival of the avalanche. This means that the resistor, R, of figure 3 now no longer plays an important role in the interruption of the discharge. Consequently, its value may be made much smaller without interfering with the operation of the counter. Actually, resistors as low as 100,000 ohms have been used with argon-alcohol counters, and 1 megohm is commonly used. This reduces the time constant of the electrical circuit attached to the wire to the order of 10^{-5} sec. For this reason vapor-type counters are often called fast counters.

A variation of the self-quenching principle has been introduced by Liebson and Friedman[3] by using a halogen gas as the quenching vapor. In this case the halogen gas performs the same role as alcohol in the Trost type of counter and in addition results in a lower starting voltage, since the halogen gas can be ionized at the expense of the energy in the metastable atoms formed in the noble gas, such as neon or argon. The metastable atoms are those that have acquired internal energy in excess of the normal without being split into ions. Using neon as the permanent gas, starting voltages as low as 400 v are obtained with a plateau of 200 to 300 v range. These counters have an indefinite life since the quenching vapor is not exhausted by use as in the case of alcohol. Also, unlike the alcohol counters, these counters are not ruined when subjected to voltages above the range of the plateau. Even continuous discharges for short periods of time do not impair this type of counter.

4. Deadtime

There is another factor that affects the recovery time of the counter that we temporarily overlooked in describing the ionization process. This is the time required for the positive ion sheath to move from the vicinity of the center wire out to a point where an electron avalanche can form. During this interval the counter is entirely dead and will not respond to primary ions formed anywhere within it. This interval is of the order of 10^{-4} sec and determines the maximum rapidity of response of the counter. The deadtime can be observed experimentally by using a cathode ray oscilloscope. This was first demonstrated by Stever.[4] When the center wire of the counter is coupled to an oscilloscope, with a sweep triggered by the pulses from the counter, a standing pattern is developed that consists of a large number of initial pulses superposed to form one pulse trace on the screen. At various intervals subsequent to this initial pulse the next observable pulse will be recorded. Since the pulses in the counter are randomly spaced these after-pulses will be at variable positions relative to the initial pulse of the particular trace recorded. The result is shown in the diagram in figure 8. There is, as expected, an interval during which no pulses appear. This is the deadtime. Beyond this interval the pulses gradually

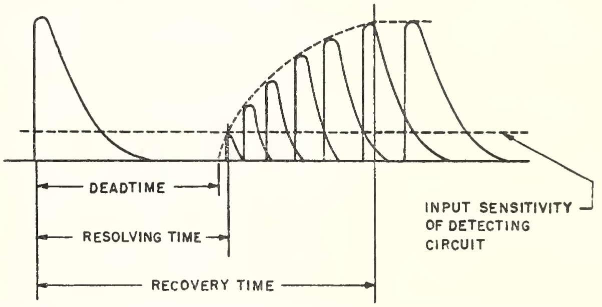

FIGURE 8. *Diagram showing the deadtime and subsequent gradual recovery of pulse size.*

build up to the original size. The time at which this has first occurred is the recovery time. In the process of increasing in size, the pulses reach a magnitude at which they will begin to actuate some recording mechanism. The time at which this occurs is the resolving time. This resolving time, usually somewhat longer than the deadtime, is the time during which the counter is unresponsive in a particular circuit. Whereas the deadtime is a characteristic of the counter itself, the resolving time depends on the sensitivity of the detecting circuit in which the counter is operating.

[3] S. N. Liebson and H. Friedman, RS I 19, 303 (1948).

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

III. Special Forms of the Geiger-Müller Counter

The Geiger-Müller counter has been made in a variety of forms for specific uses. It will detect any radiation capable of producing as much as one pair of ions within its sensitive volume. Therefore, any ionizing radiation that can penetrate to the sensitive volume either directly or by means of secondary effects can be detected with some degree of efficiency. Gamma radiation will penetrate a considerable thickness of matter, hence counters for use with this radiation can have thick metal walls enclosed in a glass tube. This type of radiation is detected by means of electrons ejected from the walls of the metal tube. Therefore, the efficiency of detection will depend on the thickness of the wall of the tube and the atomic number of the metal from which the tube is made for a given energy of gamma radiation. Beta radiation, on the other hand, is readily absorbed so that beta-ray counters must have either thin walls or a thin window through which the particles may enter. The efficiency of detection of beta particles that enter the sensitive region of a Geiger-Müller counter is practically 100 percent. Consequently, the over-all efficiency of beta-ray counters is almost completely determined by considerations of solid angles and absorption in windows, air, and the source itself.

In discussing some of the various designs of Geiger-Müller tube counters that have been used for specific purposes it will be convenient to deal with gamma-ray and cosmic-ray counters in a separate section followed by discussion of beta-ray counters. Typical examples of these various counters are shown in figures. Sufficient detail is given in most instances to permit the construction of the counters from these illustrations.

1. Gamma-Ray or Cosmic-Ray Counters

Gamma-ray and cosmic-ray counters differ essentially only in size. The low intensity of cosmic rays requires the use of larger counters than is needed for use with radioactive sources emitting gamma rays. Figure 9 shows the cross section of a glass-enclosed tube counter. For detection of gamma rays this counter would have a diameter of approximately 1 in. and an active length—length of exposed center wire—of from 3 to 10 in. Cosmic-ray counters are frequently larger in both dimensions, depending on the specific use.

It is sometimes desirable to dispense with the glass envelope. This is accomplished by using the metal tube as the container for the gas filling the counter. Figure 10 shows a gamma-ray type of counter of this kind. The center wire is supported at one end by the glass to Kovar seal at K. The other end is insulated by the glass bead B, which is supported by a wire that passes through the metal end and is soldered at A. The tube is pumped and filled through a glass tube that has been sealed off at S. Counters made in this man-

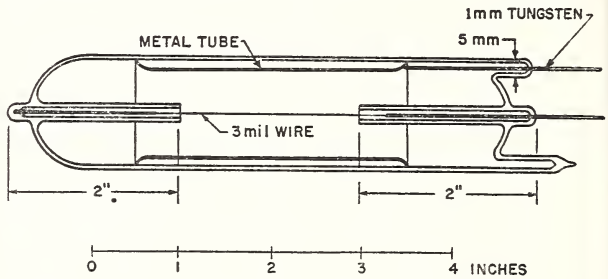

FIGURE 9. *Cross section of gamma-ray counter sealed in a glass tube.*

ner are usually operated with the tube at ground potential to minimize insulation problems and possibilities of electric shock. (See fig. 22)

The form of counter shown in figure 10 reduces the difficulties frequently encountered of sensitivity to light. The interior surface of the counter barrel often becomes photoelectrically sensitive, so that photoelectrons are ejected by light with sufficient energy to trigger the counter.

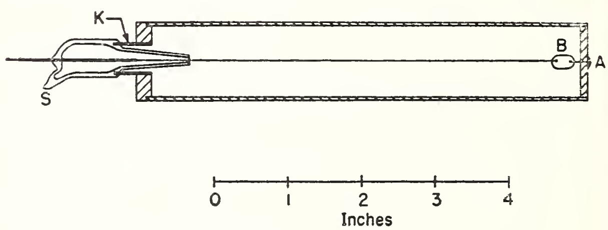

FIGURE 10. *All-metal gamma-ray counter.*

S=seal-off, K=Kovar seal, B=glass bead, A=soldered support for end of center wire.

This behavior is so prevalent that glass-enclosed counters are usually mounted in a metal housing that is light-tight. This arrangement also screens the counter from strong electrical disturbances nearby.

As has been stated, the sensitivity of gamma-ray counters is determined in part by the metal of which the counter barrel or tube is made. For gamma rays of energies of from 0.5 to 1.5 Mev, metals of high atomic number such as platinum or bismuth have considerably higher efficiency than copper or aluminum. The approximate variation of efficiency is shown in figure 11, for platinum (curve A) and copper (curve B). We will now consider some of the essential differences between beta-ray and gamma-ray counters, followed by a discussion of some particular forms of beta-ray counters.

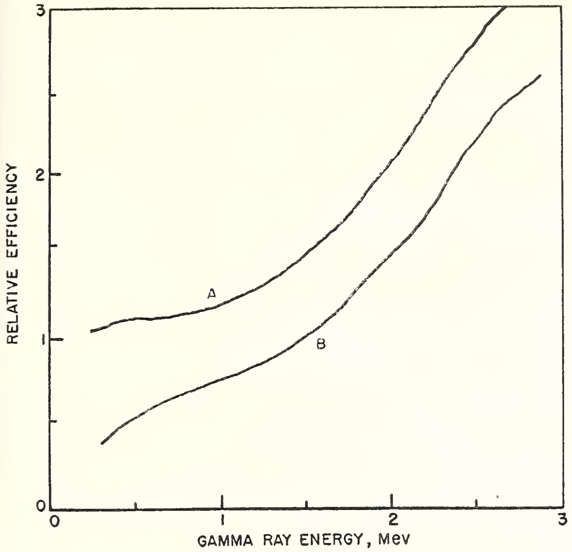

FIGURE 11. *Relative efficiencies of platinum- and copper-tube counters.*

A=platinum tube, B=copper tube.

2. Beta-Ray Counters

The measurement of beta radiation by use of Geiger-Müller counters requires modification of the form used for gamma-ray measurement. The principal change is made necessary by the lower penetrating power of beta rays. These rays are less able to penetrate matter than gamma rays of the same energy. They are formed with all energies up to the characteristic maximum energy for a particular radioisotope, therefore, even those isotopes that have a high value of the maximum energy also emit some fraction of their beta rays at very low energies. Consequently, it becomes something of a problem to design a beta-ray counter so that a large fraction of the beta rays from a given radioisotope can enter the counter.

3. Range of Beta Rays

The nature of this problem can be visualized by considering the range of beta rays of various energies. The maximum range for these particles is defined as the thickness of a medium for complete absorption. It is convenient to express this thickness in milligrams per square centimeter, since it then applies to absorbers of any material. In other words, there is very little dependence of absorption on atomic number. Figure 12 shows approximately the range (given both in mg/cm^2 and mm of Al) of beta rays of various energies up to 1.3 Mev. This curve is a linear extension of the curve shown at least up to 3 Mev. Referring to this curve, we find that a counter with walls or window with a thickness

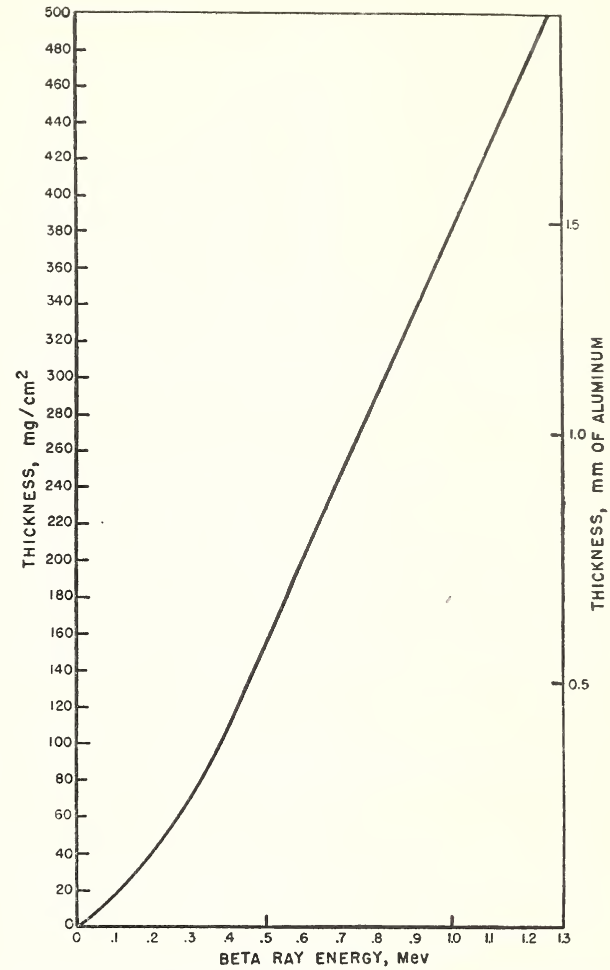

FIGURE 12. *Maximum range of beta particles of various energies.*

of approximately 130 mg/cm^2 (0.5 mm of aluminum) would not be able to detect any beta rays of energy less than 450 Kev. Similarly, beta rays of 100 Kev maximum energy would be excluded entirely by a window of about 14 mg/cm^2 thickness or about 0.05 mm of aluminum. To admit a major fraction of the beta rays from a radioisotope having a beta-ray spectrum with a maximum energy of 100 Kev would require a window having approximately $\frac{1}{10}$ the range thickness. This can be recognized from the consideration of the nature of the continuous beta-ray spectrum. The typical shape of such a spectrum is shown in figure 13. The solid curve shows the general form of the continuous spectrum. The fraction of these particles that would be detected by a counter is indicated approximately by the dotted curve for the lower energies. Depending on the thickness of the window, no particles with energies below E_{min} would be detected. A gradually decreasing fraction would be absorbed until an energy is reached where practically all particles are transmitted by the counter window.

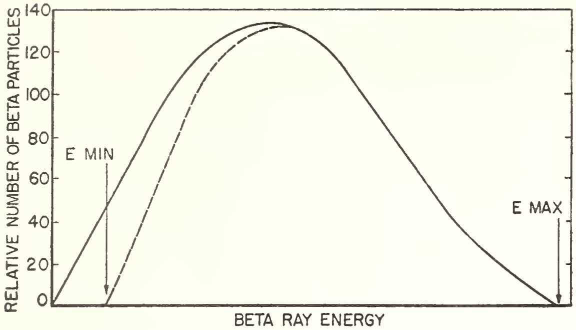

FIGURE 13. *The typical form of a beta-ray spectrum (solid curve) in relation to the portion transmitted by a thin absorber (dotted) curve.*

All particles are absorbed with energies less than E_{min}.

It is obvious that no actual counter will detect beta rays of all energies emitted by a radioisotope. Since windows with thicknesses as low as 2 mg/cm^2 can be made readily, it is comparatively simple to make counters that will detect a considerable fraction of the beta rays from isotopes having a maximum beta-ray energy as low as 100 Kev. Below this energy the problem becomes considerably more difficult.

4. Thin-Walled Cylindrical Beta-Ray Counters

One of the simplest forms of counters for use with beta rays having a maximum energy of the order of 300 Kev or higher consists of a thin-walled aluminum tube made up in a form very similar to the all-metal gamma-ray counter. Aluminum tubes of hard-drawn temper ⅝ in. in diameter and 3 to 4 in. long can be evacuated if the wall is approximately 0.004 in. in thickness. This is approximately 27 mg/cm^2. Such tubes are made commercially as toothpaste tubes. When the surfaces to be joined have been copper-plated, these tubes can be soft-soldered to appropriate fittings to convert them into a Geiger-Müller counter. The completed counter is shown in cross section in figure 14. These counters are evacuated and filled in the same way as any other Geiger-Müller counter. Although such beta-ray counters are chiefly used for survey purposes to detect beta-ray contamination, they may be used quantitatively by the technique of wrapping the source around the counter barrel in contact with it. This provides a definitely reproducible geometry, essential for quantitative measurements. This technique obviously cannot be used with sources that can leave active material on the outside of the counter tube. It is therefore limited to such uses as the counting of metal foils that have been activated by neutron bombardment or similar activation processes. Counters of this type can be made with walls quite uniform in thickness in all portions of the wall. Another important feature is that a large number of counters can be made with practically identical wall thickness. Both of these features are advantageous when counters are used for quantitative measurements.

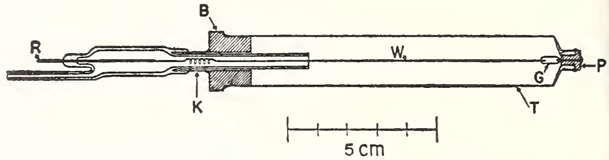

FIGURE 14. *Thin-walled counter made from aluminum toothpaste tube.*

R=Kovar wire lead, K=Kovar seal, B=brass bushing, W=center wire, G=glass bead, T=toothpaste tube, P=brass support for end of counter wire.

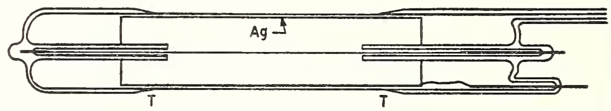

FIGURE 15. *Beta-ray counter with thin glass wall.*

Section T-T is drawn thin, and silver is deposited on the inner wall (Ag).

A somewhat less satisfactory beta-ray counter, from the standpoint of quantitative measurements, may be made by drawing the wall of a glass tube to a thickness of approximately 30 to 40 mg/cm^2 and silvering or coating the interior with a thin layer of conducting material. Counters made in this way seldom have walls of uniform thickness throughout a given counter, and this factor varies considerably from one counter to another. The thin glass wall counter is shown in figure 15.

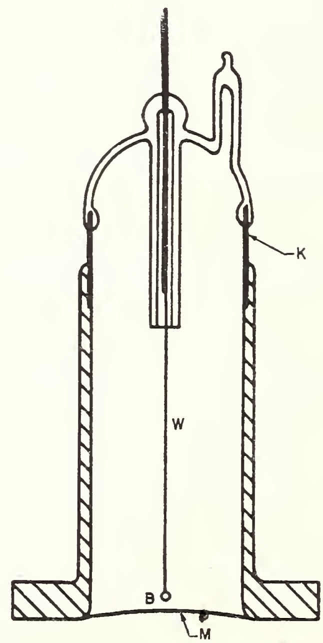

FIGURE 16. *End-window beta-ray counter.*

K=Kovar seal, W=center wire, B=glass bead, M=mica window.

5. End-Window Counter

The most generally useful beta-ray counter that has been developed to date for quantitative measurements is the bell-type, mica-window counter. A cross section of a typical bell-type counter is shown in figure 16. The mica-window is circular, usually ranging from 1 to 1¼ in. in diameter. Mica having a thickness of about 2 mg/cm^2 will stand evacuation when waxed to a supporting flange as shown over openings of these diameters. These windows can be made of very uniform thicknesses, which may be determined accurately before mounting. The circular end-window provides a definite, readily reproducible geometry, one of the fundamental requirements for quantitative measurements.

A modification of the end-window type of construction is shown in figure 17. The window at *B* consists of a concave "bubble" of glass, which is made thin enough to permit relatively soft beta rays to enter. The cathode, *C*, consists of a metal cylinder. These counters usually have a diameter of about ½ in. Their small size renders them useful in probes for locating radioactive contamination. Whereas formerly it has been customary to make these end-window counters in the laboratory in which they were to be used, a number of commercial models have recently become available. It is expected that these will improve in quality to the point where counters can be purchased which are more satisfactory than those made in the laboratory.

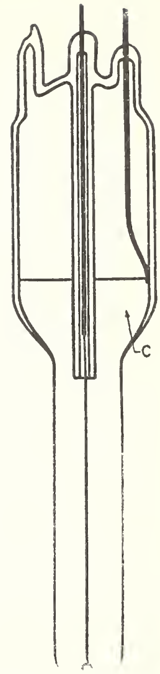

FIGURE 18. *Dipping counter for measuring beta rays from solutions.*
C=internal thin metallic coating.

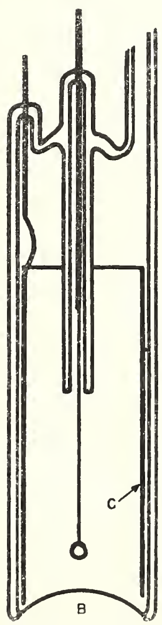

FIGURE 17. *Bubble-window beta-ray counter.*
C=metal tube, B=thin glass window.

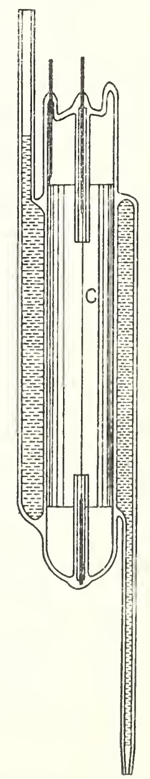

FIGURE 19. *Pipette counter for solutions.*
C=thin metallic coating.

6. Dipping and Jacketed Counters

It is sometimes desirable to measure the beta-ray activity from a solution. This can be done by use of dipping counters in some instances, or by the use of jacketed counters. Both these types have thin glass walls to admit the beta rays with an internal conducting coating to form the counter tube. The dipping counter is shown in figure 18. It combines some of the features of the end-window counter and the thin-walled glass counter. In use, the thin glass portion is immersed in the solution to be measured. For quantitative work this counter can be calibrated by immersion in solutions containing known concentrations of the radioisotope undergoing measurement. The jacketed counter is occasionally made up in the form of a pipette counter, as shown in figure 19.

IV. Methods of Detecting Counter Pulses

In the early applications of the Geiger-Müller counter and its immediate predecessors for electrical counting of particles, a string electrometer or other similar indicator for visual counting was used. It was soon recognized that the accuracy of observations could be improved, and the labor of observing and recording data greatly reduced, by use of electronic circuits for this purpose. Automatic recording circuits not only eliminate the personal error involved in observing the movement of an image of an electrometer fiber, but they permit the recording of counts at a higher rate so that the statistical accuracy of an observation made in a given time is greatly improved.

1. Mechanical Recorders

The early stages of the development of electronic counting circuits were impeded by the fact that these circuits could supply counts to a mechanical counter much more rapidly than any such device could accept and record them. Efforts were made to improve the response of mechanical recorders by making moving parts of low inertia. The practical limit to the resolving time obtained in this way falls far short of desirable performance. Also, mechanical devices operating at high speeds tend to wear rapidly and get out of adjustment.

2. Scalers

Counting of particles as a precise method of measurement received great assistance from the development of electronic scalers. Now that a variety of such scalers are readily available, in ratios that can be extended to any value necessary, counting can be made as precise as any other type of measurement, and the labor required to achieve an additional order of accuracy is no greater, and usually less, than that required in more conventional methods of measurement.

Since the scaler slows down the rate at which the mechanical counter must operate, it also lengthens the intervals between the recorded counts as compared with that of the randomly spaced counts fed into it. This results in a much more even spacing of the recorded pulses and shows that the probability of two scaled pulses arriving at the mechanical recorder in an interval shorter than its resolving time can be made very low by making the scaling ratio sufficiently large. In fact, when randomly spaced pulses are fed into a scaler with a ratio of 1:128, the scaled pulses emerge with such regularity that the ear fails to detect the variations in time between them.

In principle, a scaling circuit divides the number of pulses received by it by some fixed number. A mechanical recorder attached to the scaler then records the results of this division. The first scalers developed operated on a binary system in which the divisions were various powers of 2. The decade scalers subsequently developed from them depend on modifications of the binary principle in the use of electronic tubes.

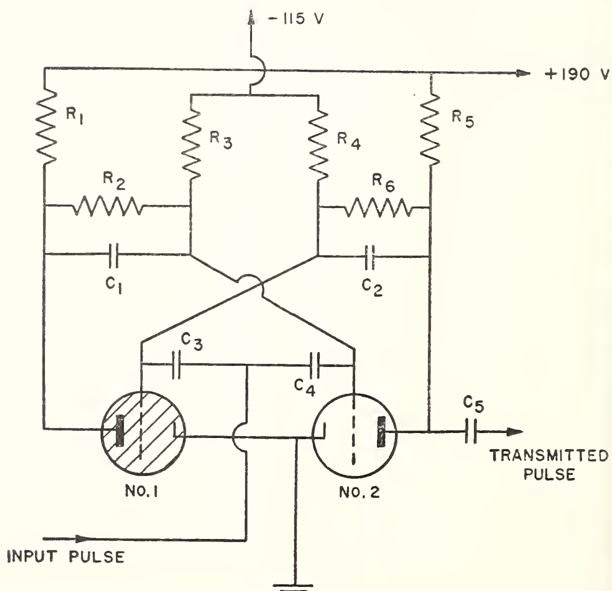

FIGURE 20. *Single Scaler Stage.*

R_1, R_5=50 K; R_2, R_3, R_4, R_6=250 K; C_1, C_2=100 $\mu\mu f$; C_3, C_4, C_5=50 $\mu\mu f$.

The fundamental elements of this binary system is a pair of vacuum tubes connected together in a network of capacitors and resistors in such a way that only one of the pair can be in a conducting state at a time. The arrangement is shown in figure 20. The associated network is adjusted so that a pulse, of proper size and shape, applied to the system extinguishes the conducting tube, permitting the other to become conducting. If we assume that this pair of tubes starts off with No. 1 conducting and No. 2 nonconducting and that a pulse will be transmitted from the pair each time No. 2 becomes nonconducting, the following operations occur as pulses arrive. The first pulse extinguishes tube No. 1 and ignites tube No. 2, the next pulse extinguishes tube No. 2, transmitting a pulse from the system and puts the pair of tubes into the initial state. Thus, for each pair of pulses received, one is transmitted. This process can be repeated as many times as desired by feeding the pulse from one scaler pair to a subsequent scaler pair. If n is the number of pairs of tubes, the input pulses are divided by 2^n.

In practice it is necessary to insert buffer stages between each scaler pair to prevent mutual interference from the various scaling stages. This buffer may be a diode or triode, which permits a unidirectional transmission of pulses. A wiring diagram of a scale-of-16 circuit is shown in figure 21. A typical input circuit is also shown, the function of which is to produce a pulse of the proper form to trip the first scaler stage. Most scalers operate only on a short or fast pulse with a steep rise. It is also customary to design the scaling stages so that a pulse of several volts is required to trip them. This renders them less susceptible to tripping by extraneous disturbances. This requires that a pre-amplifier and pulse shaper be built into the scaler to convert the pulses from the counter into a form and voltage acceptable to the scaler. It is gradually becoming the custom to include an electric timer, high voltage supply and mechanical register in the same chassis with the scaler, as shown in figure 21. This provides the complete equipment required for the operation of the counter.

In the circuit shown, the high voltage is sta-

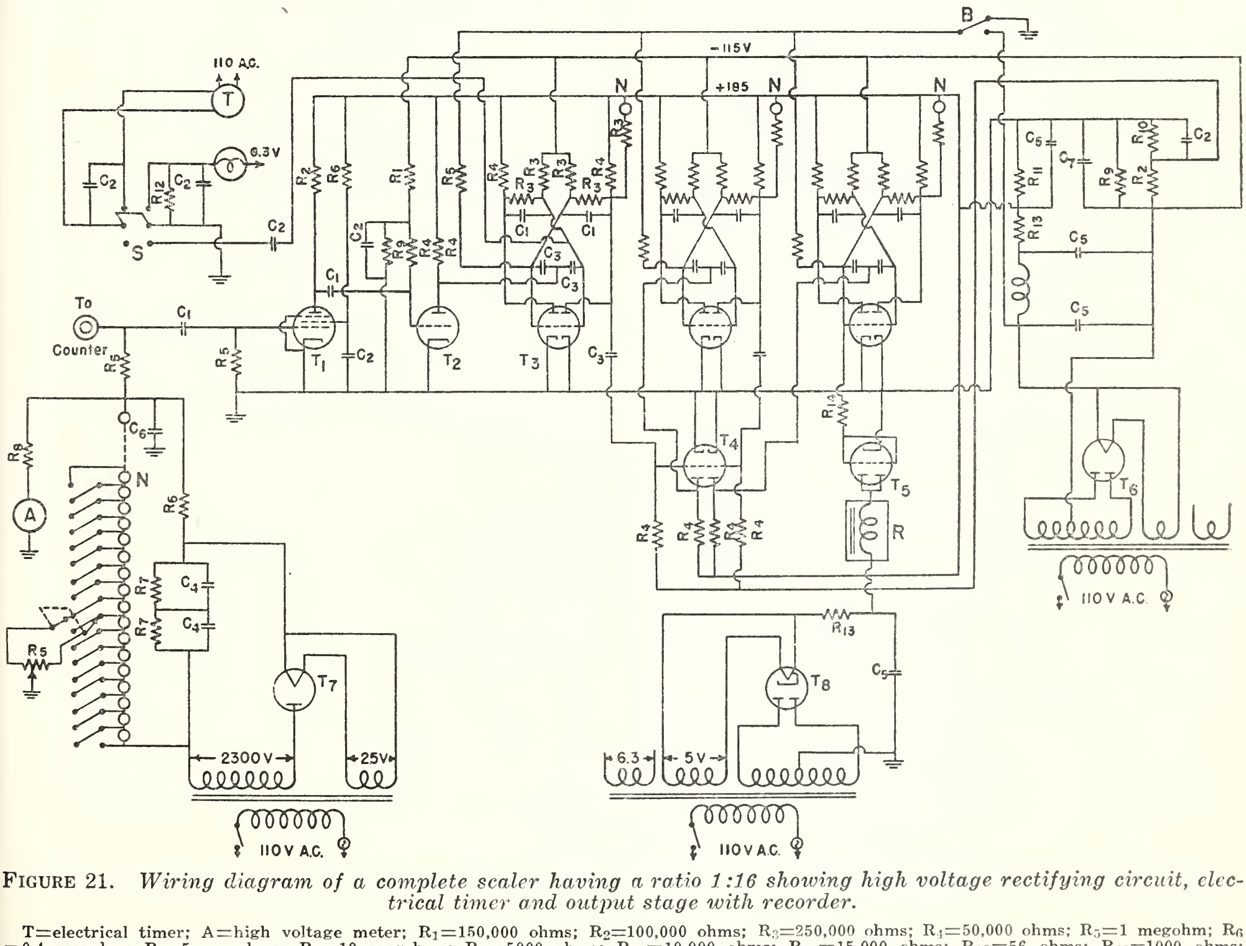

FIGURE 21. *Wiring diagram of a complete scaler having a ratio 1:16 showing high voltage rectifying circuit, electrical timer and output stage with recorder.*

T=electrical timer; A=high voltage meter; R_1=150,000 ohms; R_2=100,000 ohms; R_3=250,000 ohms; R_4=50,000 ohms; R_5=1 megohm; R_6=0.4 megohm; R_7=5 megohms; R_8=10 megohms; R_9=5000 ohms; R_{10}=10,000 ohms; R_{11}=15,000 ohms; R_{12}=56 ohms; R_{13}=1000 ohms; S=start-stop switch; R=electromagnetic register; C_1=100 $\mu\mu$f; C_2=0.1 μf; C_3=50 $\mu\mu$f.; C_4=2 μf; C_5=20 μf; C_6=0.015 μf; C_7=8 μf; T_1=6SJ7; T_2=6SF5; T_3, T_4, etc.=6SL7 or equivalent double triode; T_5=6N7; T_6=80; T_7=2X2; T_8=5Z4; N=1/25 watt neon bulbs.

bilized by means of a series of miniature neon bulbs. After aging by burning continuously on alternating current for about 2 weeks, these bulbs have a nearly constant potential across them for a range of about 0.1 to 2 ma through the bulbs. This potential on aged lamps shows only a very slight increase with time. Therefore, stabilization is accomplished by connecting the number of lamps in series to correspond to the voltage required. A protective and compensating resistor of 1 to 2 megohms is placed in series with the bank of lamps and this assembly connected across a rectifying circuit capable of supplying a voltage 300 to 400 v greater than the stabilized voltage. The switching arrangement shown in figure 21 permits the selection of any voltage less than the maximum across the whole bank of lamps. Thus, a voltage suited to the operation of a particular counter is readily obtained.

Another common method of stabilizing the high voltage for counters is by use of electronic stabilizers similar to those developed to regulate the plate voltage for vacuum tubes in amplifiers. Many of these suffer from the disadvantage that if certain of the tubes or components fail the counter voltage rises suddenly. This usually ruins the Geiger-Müller tube by applying a voltage well above the maximum of its plateau.

A number of scalers of various types are available commercially. Some include timers, registers, and high voltage supply. Others are only scalers. Most of these commercial types can be used satisfactorily with Geiger-Müller counters.

Scalers operating on the scale-of-two principle have the slight disadvantage that the reading of the mechanical register must be multiplied by the scaling ratio to obtain the actual number of counts. Since this ratio is always some power of 2, a slide rule is required for rapid computation. This multiplication is a very simple operation if the scaling ratio is some power of 10. Decade scalers having this advantage are available. They are usually based on some modification of the binary system. There are a number of ways in which the binary stages can be connected and operated to produce a scale-of-ten unit. A number of units may be placed in tandem to give an over-all ratio of various powers of 10. For example, a scale-of-ten can be produced by using three binary stages with a trigger circuit between the first two stages. This trigger circuit is made up of two tubes connected so that either one may be conducting. Pulses are fed to each grid separately, however, the grid of the first being connected to the output of the initial scaling stage and the grid of the second to the output of the third scaling stage. Starting from initial conditions with the first tube of the trigger stage nonconducting, pulses are fed through the three scaling stages in the usual manner, the trigger stage being insensitive to the negative pulses. On the eighth pulse the pulse from the last scaling stage passes through the trigger circuit, turning it over to its other stable position. This trigger circuit can now accept pulses from the initial scaling stage that are not transmitted to the two other stages. The ninth pulse is not transmitted by the initial scaling stage and the tenth merely throws the trigger circuit back to its original condition. At the same time a signal is transmitted by the trigger stage. The circuit has passed one pulse for ten entering pulses and is now back to its initial position in all respects.

3. Connections to Counters

The tubular part of a counter is operated at a negative potential. This may be accomplished by connecting this electrode to the negative of the high voltage supply. If the tubular electrode is exposed, as in all-metal counters, this presents

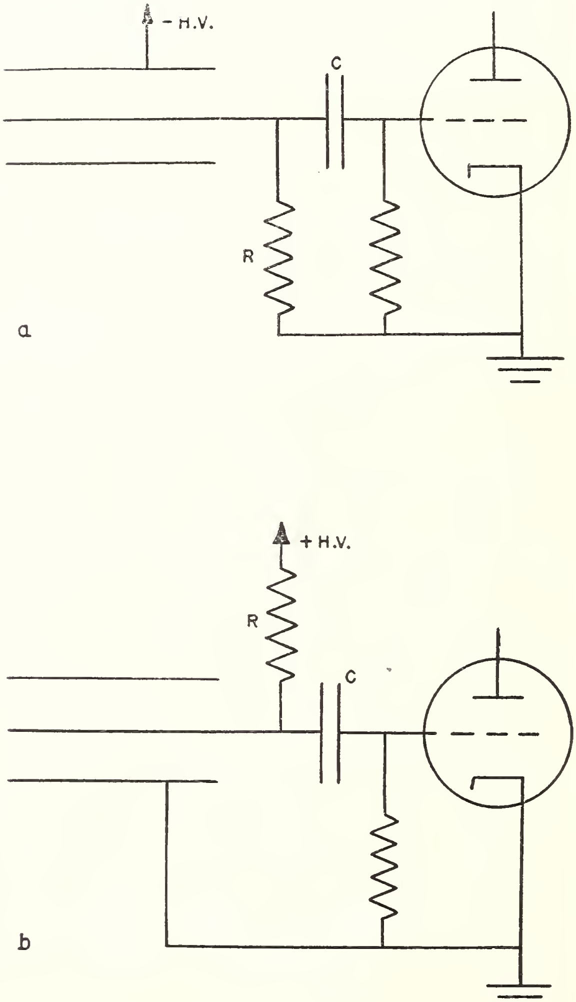

FIGURE 22. *Methods for connecting counters to the high voltage.*

(a) Negative high voltage connected directly to the counter tube; (b) Positive high voltage connected through coupling resistor to center wire with counter tube at ground potential; R=coupling resistor; C=coupling capacitor.

the necessity of insulating the counter from ground and also offers a shock hazard. When this type of connection is used a protective resistor of the order of 1 megohm should be mounted inside the cabinet of the high voltage supply. This precludes the possibility of dangerous electrical shocks.

The proper polarity can also be secured by applying the positive voltage to the center wire, in which case the coupling resistor for taking the pulse from the counter wire is in the high voltage line. Then the tubular electrode is at ground potential, which eliminates the need for insulating the counter as well as the possibility of electrical shock from external parts of the counter. These two methods of connection are illustrated in figure 22 and are equally applicable to Geiger-Müller and to proportional counters. When the second method is used a coupling condenser that can withstand the high voltage must be used.

4. Desirable Characteristics of Scalers

There are a few general considerations concerning the construction and performance of scalers that apply to any type of scaler. It is important, for example, that parts of a scaler should be well spaced to allow free ventilation. Depending on the scaling ratio, a scaler may have several dozen vacuum tubes in it that develop a considerable amount of heat. Crowding of parts results in high temperatures, which may affect the operation adversely. The scaling ratio of a scaler should be large enough so that the mechanical register is operated well below its maximum speed. This not only reduces the wear on the register but also reduces counting losses in the register. The input sensitivity should be high enough to respond to the pulses from the smallest counter used but should not exceed this requirement to the extent that it readily responds to other electrical disturbances. If a high voltage supply for the counter is included in the unit, the voltage from this source should be well stabilized. The degree of stabilization required is directly related to the slope of the plateau of the counter used. If we assume that the a-c supply may fluctuate by ± 10 percent, then the high voltage, assuming operation at 1,000 v, would fluctuate by ± 100 v without regulation. If the counter plateau has a slope of 5 percent per hundred volts, the counting rate would fluctuate by ± 5 percent. To reduce this source of error to ± 0.5 percent, for this particular counter, regulation must be introduced to keep this fluctuation in the high voltage of the order of ± 10 v, or ± 1 percent. Another important consideration is that the means of stabilization that is used for the counter voltage should not be of the type that failure of the stabilizer may result in an increase in this voltage. Many types of counters are permanently ruined if subjected for a short time to voltages that exceed that of the maximum voltage of the plateau. If a mechanical register is included it should be rugged even at the expense of a slow rate of response. The scaling ratio can be selected to operate such a register within the range of its satisfactory operation. It is also desirable that this register can be reset to zero at the end of an observation.

5. Rate Meters

For some purposes, where less precise measurements are required, an electronic device, known as a rate meter, is frequently used for indicating the output of the counter. Although rate meters can provide data of the same precision as scalers, the time required for observations to achieve this result is considerably longer. Therefore, they are chiefly used where the greatest accuracy is not required. The rate meter consists of a vacuum tube amplifier for the pulses from the counter, followed by a pulse

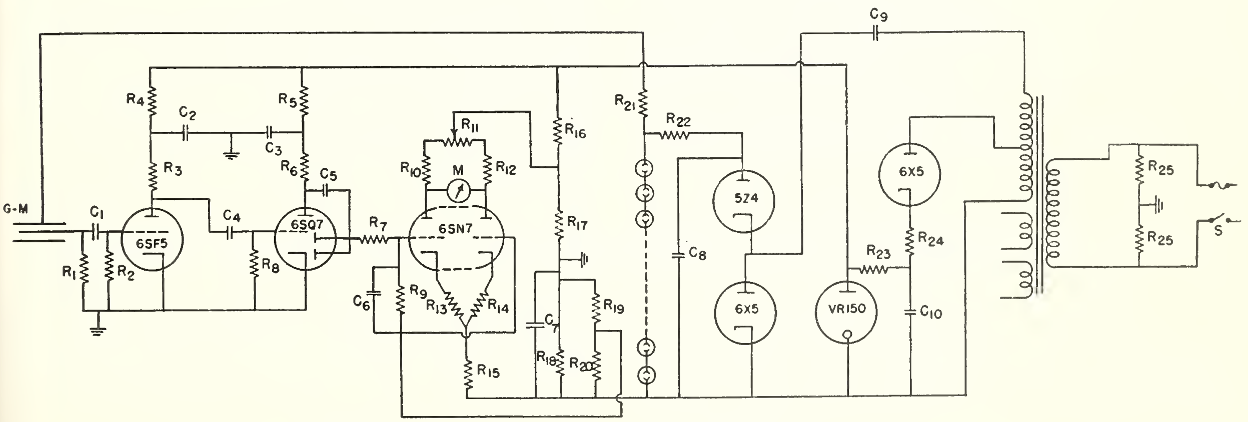

FIGURE 23. *Wiring diagram for counting-rate meter.*

R_1, R_2, R_3, R_6, R_8, R_{20}=100,000 ohms; R_4, R_5=10,000 ohms; R_7, R_{22}=1 megohm; R_9=5 megohms; R_{21}=20 megohms; R_{10}, R_{12}, R_{16}, R_{17}, R_{18}=20,000 ohms; R_{11}, R_{23}=5,000 ohms; R_{13}, R_{14}, R_{19}, R_{24}=2,000 ohms; R_{15}=50,000 ohms; C_1=100 $\mu\mu$f; C_2, C_3=8 μf; C_4=250 $\mu\mu$f; C_5=50 $\mu\mu$f; C_6=4 μf; C_7=20 μf; C_8, C_9=1 μf (2,000 volts). C_{10}=20 μf; R_{25}=100,000 ohms; S=switch; G-M=Geiger-Müller counter.

shaping circuit that makes all pulses of uniform height and shape. These pulses are then passed through a rectifying circuit from which they are fed into a condenser shorted by a suitable resistor. In operation a small uniform charge is added to the condenser for each pulse in the counter. For a constant average rate of pulses in the counter, the potential across the condenser will rise until the rate at which charge arrives is balanced by the rate at which it is lost through the resistor. The potential then will, on the average, remain constant and will be proportional to the pulse rate of the counter. To obtain a visual indication of this rate, a vacuum tube voltmeter is connected across the condenser. The indicating meter of this unit can be calibrated directly in terms of the rate of pulses entering the input of the rate meter. A wiring diagram of a typical rate meter circuit is shown in figure 23. A photograph of a rate meter built from this circuit is shown in figure 24.

The accuracy of observations by means of rate meters is limited by the statistical fluctuations in the pulse rate of the counter. Radioactive radiation is emitted in random directions and is also random in respect to time. As will be shown later, the accuracy depends upon the number of pulses included in an observation. When using scalers this number can be increased at will usually merely by extending the period of observation or using a stronger source. In the case of rate meters this factor is controlled in part by the time constant of the integrating condenser circuit. It can be extended by taking frequent readings of the meter at intervals. This is time-consuming and does not readily lend itself to improving the accuracy. Therefore, the rate meter has come to be used for purposes where a more or less instantaneous reading yields results of sufficient accuracy. Among typical uses may be mentioned health survey, detection of contamination and in prospecting for ores. Rate meters have been constructed which operate entirely from dry batteries and which have a total weight of 5 or 6 lb. These devices are completely portable and therefore can be used to locate regions where the level of radiation is considered dangerous. Only a qualitative indication can be obtained in this way. This is frequently helpful information. When used with appropriate Geiger-Müller counters portable forms of this instrument may be used to locate radioactive contamination either by means of its beta or gamma radiation. Most uranium ore worth mining has sufficient activity so that it can be identified by a Geiger-Müller counter. Therefore, portable rate meters have been useful in explorations for sources of uranium ores. For greater portability, the integrating circuit and vacuum tube voltmeter are often eliminated by substituting headphones to count the pulses directly. This is satisfactory in prospecting where the intensities encountered are usually low. A wiring diagram of such a portable, battery-operated device is given in figure 25.

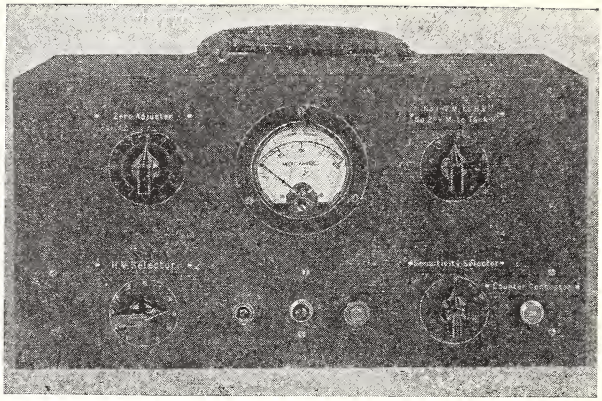

Figure 24. *Exterior view of counting-rate meter.*

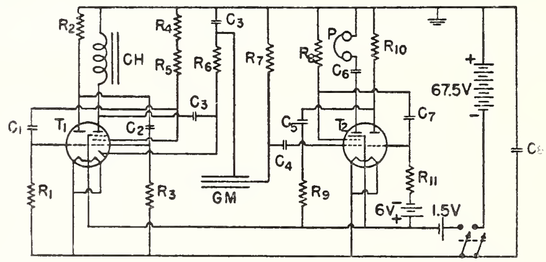

Figure 25. *Wiring diagram of battery operated portable counting circuit.*

R_1, R_3, R_9, R_{11}=0.5 megohm; R_8, R_{10}=0.1 megohm; R_2, R_5=1 megohm; R_4=5,000 ohms; R_6=20 megohms; R_7=40 megohms; C_1, C_2, C_4, C_5, C_6, C_7=0.01 μf; C_3=0.03 μf (2,000 volts); C_8=8 μf; T_1, T_2=3A8GT; CH=100 henry choke; G-M=Geiger-Müller counter; P=headphones. [W. Hushley & K. Feldman, Canadian J. Res., vol. F25, P226, 1947.]

V. Applications of Counters to Quantitative Measurements

1. Statistical Fluctuations

Whenever measurements of a specified accuracy are required of a Geiger-Müller counter, the errors that are introduced by the random nature of radioactive radiations must be considered. These errors are computed in terms of the standard deviation of a counting observation defined as the square root of the total number of counts in a single observation. This standard deviation means that a deviation of 0.6745 times the standard deviation is as likely to occur as not, that is, will occur on the average in 50 percent of the observations. A deviation of twice the standard deviation will occur in only about 5 percent of the observations. Actually, the standard deviation increases with the number of counts recorded in an observation. The relative standard deviation, however, decreases. Thus, if N is the total number of counts in an observation the standard deviation is $\sqrt{N}$. The ratio $\sqrt{N}/N$ decreases as N becomes larger. For example, for 100 counts $\sqrt{N}=10$, $\frac{\sqrt{N}}{N}=1/10$, but for 10,000 counts, $\sqrt{N}=100=\frac{\sqrt{N}}{N}\neq 1/100$. Expressed in percentages of N, we have a standard deviation of 10 percent in the first example and 1 percent in the second. There are obviously two ways of increasing the number of counts in the observation—one is by increasing the counting rate by using a stronger source or moving the source nearer the counter, and the other is by prolonging the time of the observation. This choice is not always available, and occasionally the accuracy of counting observations is limited by the statistical fluctuations.

2. Resolving Time

The deadtime of a counter is illustrated graphically in figure 7. This figure also shows the relation between the deadtime and the resolving time. The resolving time is of importance in the use of the counter, since it determines the number of counts that fail to be recorded due to the fact that two closely spaced counts may be recorded as a single count. Reference to figure 7 shows that the resolving time is longer than the deadtime. The magnitude of the difference is determined by the sensitivity of the detecting circuit to which the counter is attached. Therefore, resolving times must be determined for the counter with the detecting circuit used with the counter.

There are various methods for determining the resolving time of counters and associated equipment. One of the simplest, which is adequate for most purposes, involves the use of two sources of the same order of activity but not necessarily equal. If we designate the sources by A and B, the procedure is as follows: source A is placed in a fixed position relative to the counter and the counting rate determined, which we will call n_1 counts per minute. Without disturbing A, the source B is placed at another fixed position in relation to the counter and the counting rate for $A+B$ determined, which we will call n_3 counts per minute. Finally, source A is removed without disturbing B, and the counting rate obtained is called n_2 counts per minute. If the intensity of $A+B$ is sufficient to give a counting rate such that a significant number of counts are lost due to lack of resolution, we will find that $n_1+n_2>n_3$. Therefore, $n_1+n_2=n_3+\delta$. The resolving time t_r is then given to a very close approximation by

$$t_r=\frac{\delta}{2\,n_1\,n_2-\delta\,n_3/2}.$$

When δ is small compared to n_1 and n_2, this reduces to

$$t_r=\frac{\delta}{2\,n_1\,n_2}.$$

The effect of this resolving time is to render the counter insensitive for a certain fraction of the time it is in operation. If the average true counting rate per second for an observation is n_t, then the insensitive time per second is $n_t\,t_r$, both quantities being expressed in terms of seconds. The average number of counts lost per second is $n_o\,(n_t\,t_r)$ if n_o is the observed average counting rate. The true counting rate is the sum of the observed and lost counts, or

$$n_t=n_o+n_o\,(n_t\,t_r),$$

from which

$$n_o=\frac{n_t}{1+n_t\,t_r}.$$

It is more convenient to use this relation when solved for n_t, which gives

$$n_t=\frac{n_o}{1-n_o\,t_r}.$$

The effect on the measurements can be made clearer by a few numerical examples. Let us assume that $t_r=10^{-3}$ sec. For an observed counting rate of 10 counts per second, the true rate is 10.1 per second; but for 100 counts per second the true rate is 111, so that the error from lost counts has risen from about 1 to 11 percent.

The lower limit of the resolving time is the deadtime of the counter. It is advantageous to use counters of short deadtime. However, the value of this time for usual Geiger-Müller counters is not less than about 5×10^{-4} sec. Therefore, counters must be operated at rates where this time introduces negligible error, or a correction must be computed for the measurements using the measured resolving time for this purpose. These corrections may be obtained from the graph shown in figure 25a.

3. Absorption of Beta Rays

Beta-ray counters are frequently used for quantitative measurement of disintegration rates. This procedure is based on the assumption that all beta particles of a source which disintegrates exclusively by emission of beta rays are detected for a known solid angle. The solid angle is usually determined by comparisons of response of the counter with several sources of known disintegration rate or by computation, using the dimensions of the source and counter window and the distance separating them. We have seen, however, in discussing the absorption of beta particles, as illustrated by figure 13, that all the particles emitted by the source in the solid angle subtended by the counter cannot enter the counter. A certain fraction is lost by absorption. The magnitude of this fraction will depend on the thickness of the window and of the intervening layer of air as well as on the value of $E_{\max}$ and the specific shape of the spectrum. To obtain the true disintegration rate of the source, a correction must be applied to the observed data for the particles of low energy that are not detected. The simplest way to obtain this correction is by use of a standard preparation of the radioisotope under measurement.

4. Back-Scattering of Beta Rays

An equally serious problem is encountered in connection with scattering of the beta particles. These particles are easily deflected on collision with atoms. In some cases the particles are scattered backwards, the amount depending on the atomic number and thickness of the scattering layer. Consequently, if a radioactive source is mounted on a substantial metal support a considerable fraction of the particles counted will be those that were not emitted in the direction of the solid angle subtended by the counter at the source. These extra particles falsify the measurement. For absolute measurements of disintegration rates, efforts must be made to eliminate this back-scattering or to determine the proper correction for it. Even in comparative measurements it is essential that the back-scattering be kept constant by using the same thickness of the same material for supports of all sources. Since any support that produces negligible back-scattering is fragile it is more convenient to use a thickness that will produce saturation back-scattering. This is obtained by making the thickness of the support equal to, or greater than the range of the beta particles from the source under observation. For a given radioisotope the saturation back-scattering will be proportionally the same for all sources.

5. Coincidence Counters

One of the advantages of counters, arising from the fact that they detect individual particles or photons in an almost instantaneous manner, is that they can be used to determine the relative number of such particles that occur simultaneously from a given source. Coincidences between two gamma rays, a beta ray and a gamma ray, or two beta rays can be determined by use of appropriate counters and appropriate electronic circuits. This property of counters is useful in studying disintegration schemes where it is desirable to know how the gamma rays are associated with the beta rays. This may be illustrated simply by assuming that it is known from other investigations that a particular radioisotope emits two beta rays β_1 and β_2 and three

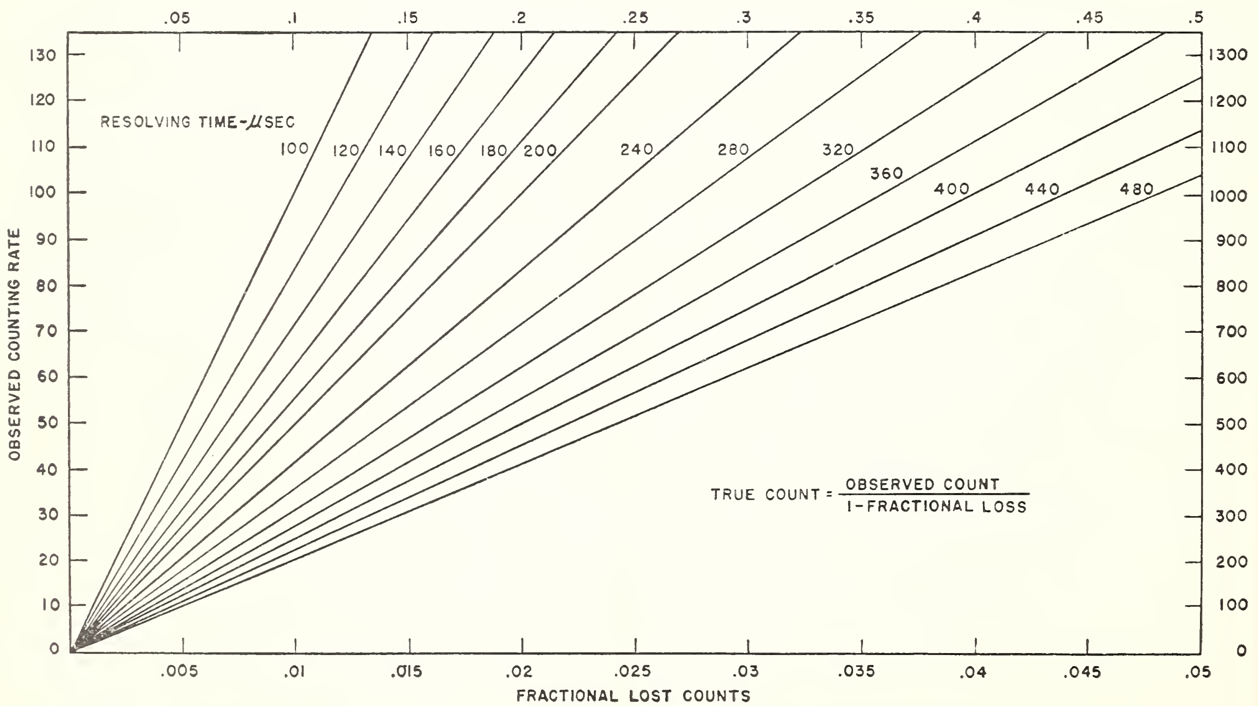

FIGURE 25a. *Fractional lost counts for different resolving times and for a wide range of observed counting rates.*

The true counting rate is equal to observed counting rate as shown on the y-axis multiplied by (1-Fractional Lost Counts) where the fractional lost counts is read on the x-axis for the resolving time in question.

gamma rays γ_1, γ_2, and γ_3. The nature of the disintegration scheme and the total energy of disintegration depends on the relation of the gamma rays to the beta rays. For example, if it can be shown experimentally that there are no coincidences between β_1 and γ_1 but there are coincidences between β_1 and γ_2 as well as coincidences between γ_2 and γ_3, we know that these gamma rays are associated with β_1. If it is further confirmed that there are coincidences between β_2 and γ_1 and no coincidences between γ_1 and γ_2 the picture is complete providing the measured energies of the various components agree. The above assumptions lead to the conclusion that the energy of β_2 plus the energy of γ_1 should equal the sum of the energies of $\beta_1+\gamma_2+\gamma_3$. The disintegration scheme then may be represented by the diagram in figure 26.

A block diagram of equipment for determining β-γ coincidences is shown in figure 27. The source is placed in a fixed position between a beta-ray and a gamma-ray counter. This simple arrangement in itself will not determine which gamma rays are coincident with a given beta ray. To obtain this information either absorbers must be introduced between the source and each counter to reduce or eliminate the effects of radiation of a given energy, or the whole experiment performed in a magnetic focussing device that separates the effects of the beta rays, assuming that more than one is present.

The electronic circuits used to detect coincidences most commonly used are based on the method developed by Rossi.[5] The basic principle of this method is illustrated by the diagram shown in figure 28. The vacuum tubes 1 and 2 are connected to the counters GM-1 and GM-2 through a resistance-capacity input. The tubes 1 and 2 are arranged to be normally in a conducting state. A pulse from either counter will produce a negative potential on the grid of the associated vacuum tube. This produces a sudden reduction in the plate current of the vacuum tube, which results in a voltage pulse at the plate. The two plates are connected in parallel so that the pulse on the conductor connecting these plates is at least twice the size when both 1 and 2 receive negative pulses simultaneously, that is when one or the other receive pulses at different times. The bias on the grid of tube 3 is adjusted so that it responds only to the large pulses produced when pulses occur simultaneously in both counters.

In practical measurements each counter will deliver a large number of random pulses in addition to those that happen to occur simultaneously. Therefore, there is a probability that some of these random pulses coincide and produce a false or accidental coincidence. This probability

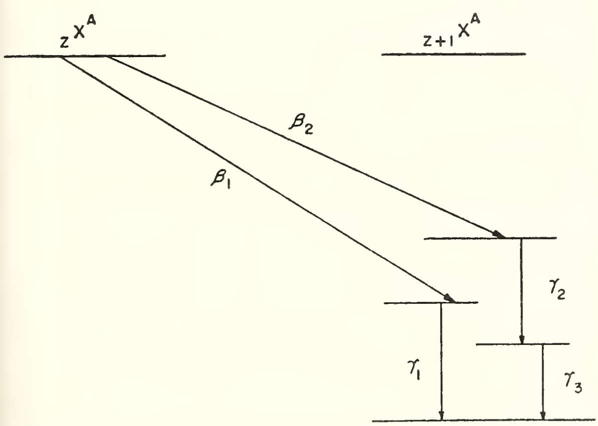

FIGURE 26. *Typical disintegration scheme for a radioisotope of atomic number Z and mass number A which disintegrates by emission of beta rays, β_1 and β_2 of two different maximum energies to form the radioisotope of atomic number Z + 1 and mass number A.*

β_1 is followed by emission of one gamma ray γ_1 and β_2 by two gamma rays γ_2 and γ_3.

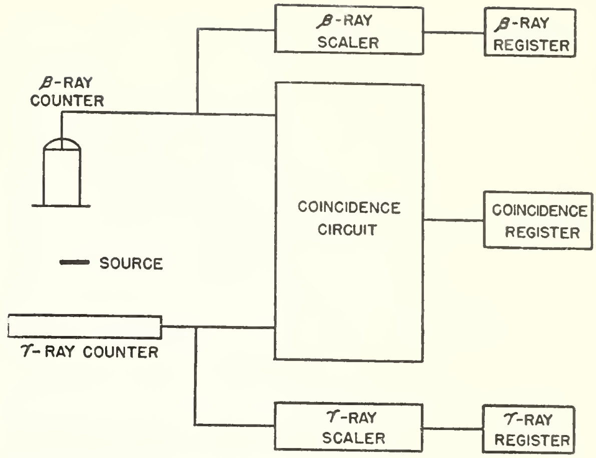

FIGURE 27. *Block diagram of a coincidence circuit for determining coincidences between beta and gamma rays.*

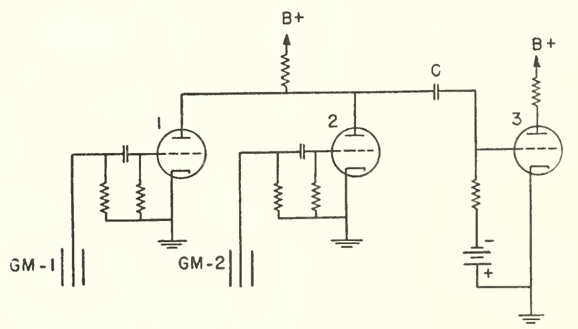

FIGURE 28. *Basic Rossi circuit for determining coincidences between two Geiger-Müller counters, GM-1 and GM-2.*

A pulse in either tube 1 or 2 does not decrease the negative grid voltage of tube 3 sufficiently to cause it to transmit a pulse. When pulses occur in both 1 and 2 simultaneously a pulse is transmitted by tube 3.

[5] B. Rossi, Nature 125, 636 (1930).

depends on the counting rate in each counter and also on the interval of time that must separate two pulses in order that they fail to produce a coincidence. This interval is called the resolving time of the coincidence circuit. It depends upon the constants of the coincidence circuit and the shape of the pulses. Therefore, in building coincidence circuits, the simple arrangement of figure 28 is rarely used. The pulses from the counters are sharpened and made of uniform height so that when they arrive at the coincidence tubes 1 and 2, they are all of uniform height and width. The resolving time of the circuit can then be made of the order of 1 microsecond.

The number of accidental coincidences is given by the relation

$$A=2\, n_1\, n_2\, t,$$

where A is the number of accidental coincidences, and n_1 the number of counts in counter number 1, and n_2 the number of counts in counter number 2 all referred to the same interval of time. The resolving time is denoted by t. If we consider a possible case in which counter number 1 has an average rate of 500, and counter number 2, 5,000 counts per minute and assume $t=10^{-6}$ sec, we find that the rate of the accidental counts on the average is

$$A=2(5\times10^2)\,(5\times10^3)\,10^{-6}=5 \text{ per minute.}$$

In a coincidence experiment made under these conditions this number of counts must be subtracted from the observed coincidences.

Another correction must be applied to the observations before the true number of coincidences is obtained if we are interested in those produced by a source of radioactivity. These are the real coincidences that arise from cosmic rays. It is impossible to shield the counters, completely, from the effects of cosmic rays. A geometrical arrangement may be adopted, which is less favorable to the detection of coincidences caused by cosmic rays. The intensity of cosmic rays is greater in a vertical direction than in any other and has a minimum in the horizontal direction. Therefore, it is preferable to place the counters in a horizontal rather than a vertical alinement. The number of cosmic-ray coincidences will also depend on the size of the counters. The lower limit for these coincidences is of the order of 0.03 per minute, using counters about 2 cm in diameter and 4 or 5 cm long in a horizontal alinement. Under less favorable conditions this rate can be considerably higher. The above figure refers to observations near sea level, and at higher altitudes this will be increased with the well-known increase of cosmic-ray intensity with altitude.

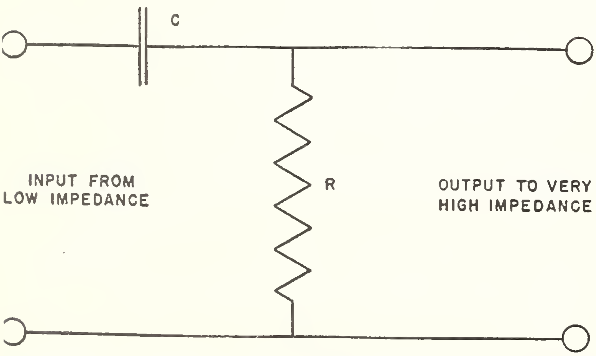

FIGURE 29. *Diagram of a filter circuit for electrical differentiation of a pulse.*

Various methods have been devised for converting the pulses provided by Geiger-Müller counters into a form suitable for use in a coincidence circuit. One method is to use a multivibrator modified to deliver one pulse for each input pulse. A simpler method, which is adequate for many purposes, is to employ electrical differentiation. This procedure is described by Lewis.[6] If a slow pulse, say of 10^{-4}-sec duration, is passed through a resistance-capacity filter of the form shown in figure 29, in which the time constant, RC, is made short compared with the desired resolving time, the pulse will be converted into a sharper form trailing off in a long tail. This process can be repeated as illustrated in figure 30. At "A" two pulses are shown, one solid and one dotted, which have a duration of about 10^{-4} sec but which are displaced along the time axis by approximately 4 microseconds. Here the two voltage peaks are not resolved since the dotted pulse rises to close to the maximum before the pulse represented by the solid curve has fallen noticeably. When these pulses have been passed through the filter circuit they will have the form shown at "B," where a slight sepa-

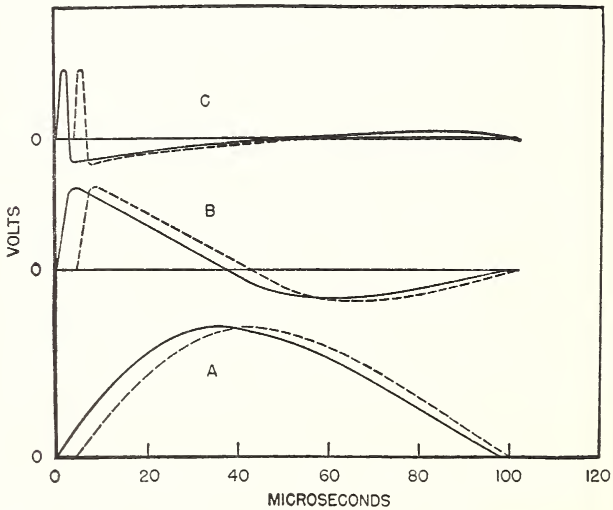

FIGURE 30. *Diagram of the successive differentiation of an electrical pulse.*

A shows two pulses prior to differentiation and B shows the effect of one differentiation; C shows them after a second differentiation.

[6] W. B. Lewis, Critical Counting (Cambridge Univ. Press, 1943).

ration of the two peaks is evident. On passing these pulses through a second similar filter, the forms shown at "*C*" are obtained, where they are clearly separated. The variation in pulse heights can be levelled by appropriate electronic circuits, and the effect of the low amplitude after pulse shown at about 80 microseconds can be eliminated by suitable bias. When pulses of the order of a microsecond result from differentiation of pulses that have a duration of the order of 10^{-4} sec, the amplifier used must have a reasonably constant amplification over a wide band of frequencies extending from less than 10^4 to well above 10^6 cycles per second. Great care is required in the selection and location of components in amplifiers of this type. However, for coincidence counting strict linearity is not required. It is desirable that pulses arriving at the mixing stage of the Rossi coincidence circuit have the same height regardless of their heights at intermediate points between this stage and the Geiger-Müller counter. This can be provided, for example, by amplifying all pulses so that the smallest will throw the grid of one of the intermediate vacuum tubes to cut-off, giving sensibly uniform pulses at the plate of this tube.

A wiring diagram of a coincidence circuit constructed on the principle of electrical differentiation is shown in figure 31. Approximate values for the various constants are given in the legend for the figures. The functioning of any actual circuit made up in this form must be tested by examining the pulses at various points with a cathode ray oscilloscope. Components are changed or relocated until satisfactory performance is obtained.

6. Cosmic-Ray Counters

The Geiger-Müller counter has been used extensively in cosmic-ray investigations, not only because it is one of the most sensitive devices for detecting this radiation but also because directional observations are possible with assemblages of counters connected to coincidence circuits. Similar arrangements can be used to observe absorption of cosmic rays and to study the composition of cosmic-ray showers. The counters used for this purpose do not differ basically from gamma-ray counters. The size of counters used may vary from approximately an inch in diameter and a few inches in length up to several inches in diameter and several feet in length.

Coincidence counting is very common in cosmic-ray observations as by the use of three or more counters connected to count in coincidence and arranged with the axis in the same plane if a well-columinated beam of radiation is selected for observation. At the same time random counts of various origins are excluded from observation except as they contribute to the accidental coincidence rate. The coincidence circuits used in these observations are similar in principle to those used in studying coincidences of radioactive radiations. It is obvious that the simple two-counter circuit described for that use can be extended to several counters.

A modification of the coincidence technique is known as anticoincidence counting. This consists of connecting an additional counter or counters to the coincidence circuit, arranged to produce a pulse of opposite sign on the grid of the mixing tube to that produced by the coincidence counters. This will cancel any coincidence pulse that arrives at the same time. When the anticoincidence counter produces a pulse in the absence of a coincidence pulse, no response is produced in the mixing tube. Therefore the circuit as a whole responds only when coincidences occur in the coincidence counters, and no pulse is produced in the anticoincidence counters. An example of the use of this method is the selection of single cosmic rays, not associated with showers, for observation. If one or more counters are mounted outside the bank of counters used to observe coincidences and connected in anticoincidence, then the arrangement responds only

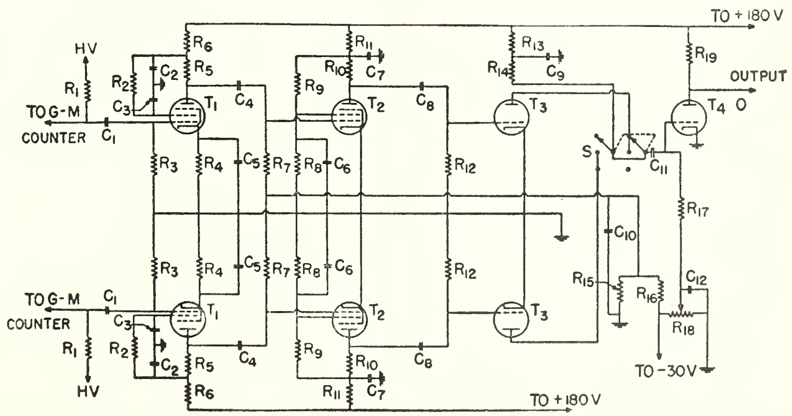

FIGURE 31. *Wiring diagram of a coincidence circuit using electrical differentiation for sharpening the pulses.*
C_1=50 $\mu\mu f$; C_2, C_7, C_9=2 μf; C_3, C_6, C_{10}, C_{12}=0.1 μf; C_5=0.01 μf; C_4=43 $\mu\mu f$; C_8=25 $\mu\mu f$; C_{11}=25 $\mu\mu f$; R_1=1 megohm; R_2=0.1 megohm; R_3, R_{14}=0.5 megohm; R_4=2,200 ohms; R_5, R_7, R_{10}=25,000 ohms; R_6, R_{11}, R_{13}=5,000 ohms; R_8, R_9, R_{12}, R_{16}, R_{18}, R_{19}=50,000 ohms; T_1, T_2=6AK5; T_3=6SF5; T_4=6SJ7.

when single rays traverse the coincidence bank and no pulses occur in the anticoincidence counters. This eliminates those particles that are part of showers that would also produce pulses in the anticoincidence counters. The uses to which this principle may be put are numerous and are not confined to cosmic-ray observations.

The basic idea of the anticoincidence method is illustrated in figure 32. The three counters marked *C* are connected in the usual coincidence arrangement. To provide a pulse of the opposite sign from the anticoincidence counter *A*, an extra vacuum tube is inserted in the line connecting this counter to the circuit. Therefore, this counter will produce a pulse on the grid of the mixing tube, *M*, which cancels a coincidence pulse arriving at the same time. The bias on the grid of the mixing tube is arranged to produce no effect when pulses from the anticoincidence counter alone arrive at this stage. The result is that coincidences are recorded only when a particle traverses the three coincidence counters in the absence of a particle through the anticoincidence counter.

VI. Proportional Counters

Almost any type of Geiger-Müller counter may be operated as a proportional counter. However, in general, proportional counters are usually filled with gases or mixtures that would not give satisfactory operation as Geiger-Müller counters. The close relation between the two types of counters can be understood by examining what occurs in the counter as the potential across it is raised in steps from a value of around 50 v up to that required for operation as a Geiger-Müller counter. At the low voltages it is found that ions produced in the gas of the counter are merely collected. No new ions are formed so that the primary ions of one sign produced by radiation are collected on the wire, the others travelling to the cylinder. Since some ions recombine during this interval, actually not all of the primary ions are collected. Conditions may be arranged to reduce this loss to a minimum. Therefore, at this voltage the counter operates as an ionization chamber. If the voltage is raised to a few hundred volts, it is found that distinct pulses appear corresponding to many more ions than were produced in the primary ionization process. These additional ions have been produced as the result of the acceleration of the primary ions in the electric field. When they have reached velocities that provide them with the amount of energy required to ionize atoms of the gas they may produce a new pair of ions.

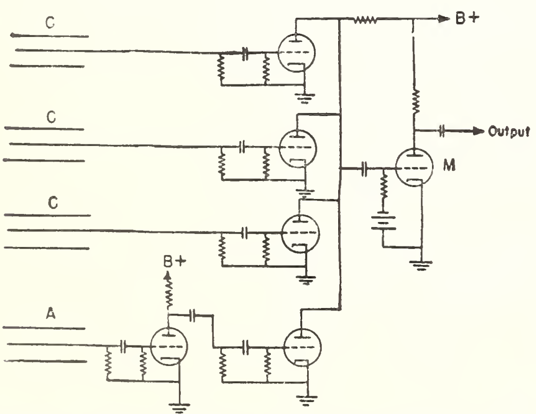

FIGURE 32. *Anticoincident circuit; CCC=coincidence counters, A=anticoincidence counter.*

This process may be multiplied many times before those ions proceeding toward the wire have reached it. This process is called gas amplification. The amount of this amplification in a specific case will depend on a number of factors, such as the nature and pressure of the gas, the dimensions of the components of the counter, and the voltage applied to it. In the average proportional counter a gas amplification of about a thousand may be obtained. In this region it will be found that the size of the pulses are proportional to the number of primary ions. Hence, this is the proportional region, and the counter operates as a proportional counter. Alpha particles produce large pulses and beta particles much smaller pulses. Gamma rays produce an almost undetectable effect.

If the voltage across the counter is increased to the order of 1,000 v, a change is noted in the pulses. They become much larger and very nearly uniform in size, at a given voltage, regardless of the primary ionization. Gamma-ray, beta-ray, and alpha-particle pulses are indistinguishable. This is the Geiger region, previously mentioned. This is illustrated in figure 33, where two curves are plotted, one showing the logarithm of the two pulse sizes for gamma rays and alpha rays, the other showing the logarithm of the ratio of these pulses. The figures on which these curves are based are arbitrarily selected from possible values and are used merely to illustrate qualitatively the distinction between pulses produced only by primary ions, those resulting from proportional gas amplification, and Geiger-Müller pulses. In the range up to about 400 v, only primary ions are collected; from 400 to 800 v, pulses are proportional to the number of primary ions; and above 1,100 v the size of the pulse is independent of the number of primary ions. In the Geiger-Müller region the pulses grow in size in proportion to the over-voltage but, since we have plotted the logarithms to bring the graph to a convenient scale, this increase is scarcely noticeable in the curve.

Actually there is a region of transition between each particular type of operation. The sharpness of the transition depends on the various factors that control the operation of this type of device. In the construction of proportional counters the components are arranged to provide proportional characteristics over a considerable range of voltage. This is accomplished by making the diameter of the center wire or electrode with a radius large compared to that used in Geiger-Müller counters and by choosing a filling gas and pressure that contributes to the stability over a large range of voltage.

1. Construction of Proportional Counters

The actual form of a proportional counter depends in part on the use that is to be made of it. A few typical designs are given that will illustrate some of the possible forms.

Some proportional counters are only slight modifications of the Geiger-Müller counter. They have the conventional tubular cathode with a center wire usually several times the radius of that regularly used in Geiger-Müller counters. They are filled with an appropriate gas at a considerably higher pressure than is used in the Geiger-Müller counter. This pressure may be anything from greater than atmospheric pressure down to a quarter of an atmosphere. Since these counters can be operated at atmospheric pressure a window of greater size can be used. This choice is frequently made, since it permits the use of thin windows of larger size. If it is desired to operate them at relatively low voltages, helium or argon may be used as a filling gas.

Proportional counters can be made in two general types. One is similar in construction to the Geiger-Müller tube counter. It differs essentially from the tube counter only in the pressure of the gas used in filling it. To detect the pulses produced in the proportional region it is necessary to use a more sensitive amplifier that should give a linear amplification over a considerable range of input pulses. This linearity is necessary if full advantage is to be taken of the proportional amplification in the counter.

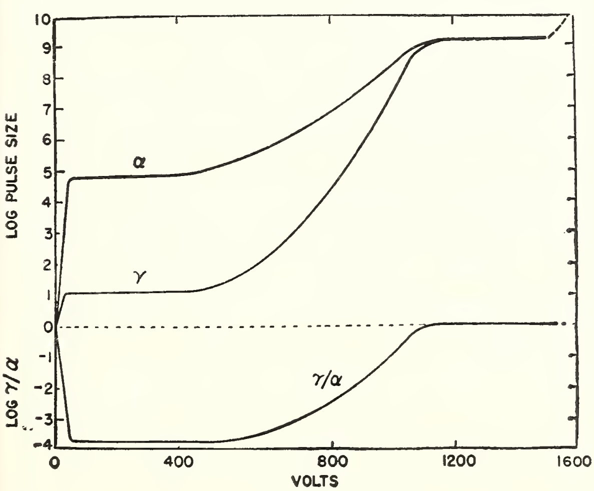

FIGURE 33. *Curves showing the relation of pulse sizes from alpha particles and gamma-ray photons for various voltages on a counting tube.*

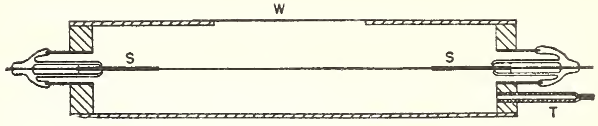

FIGURE 34. *Tubular proportional counter.*

W=thin window; SS=metal shields to define the effective length of the center wire.

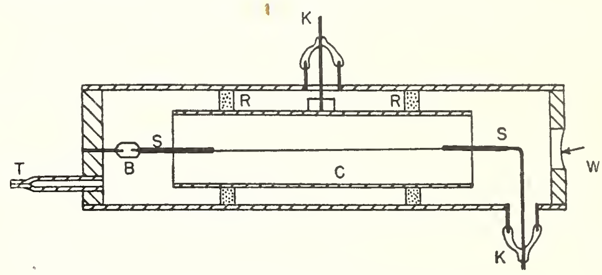

FIGURE 35. *End-window proportional counter.*

C=metal tube; RR=supporting insulating rings; B=glass bead; SS =metal shields; K=Kovar seals; W=thin window; T=tube for filling and scaling.

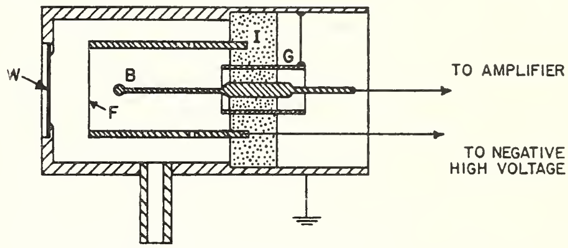

FIGURE 36. *Proportional ball counter.*

B=metal ball; F=metal foil; I=insulator; G=guard ring; W=thin window.

Figure 34 shows a typical tubular type of proportional counter, provided with a thin window, *W*, on one side of the tube. A thin window proportional counter offers the possibility of counting alpha particles and protons in the presence of beta and gamma rays. The pulses from the different types of radiation can be distinguished as a result of differences in the number of ions per centimeter produced in the primary ionization by these particles. The discrimination is usually accomplished electronically by a suitable bias in the detecting circuit that excludes the small pulses produced by beta and gamma rays.

An end-window form of the proportional tube counter is shown in figure 35. The radiation to be detected enters the window at *W*. The cathode *C* is supported by insulating rings, *RR*, so that the housing may always be maintained at ground potential. This type of counter may be filled and sealed permanently by means of the copper tube T.

Another form of proportional counter is the ball-counter shown in figure 36. The central electrode terminates in a polished metal ball 1 to 2 mm in diameter. The cathode cylinder has a thin aluminum foil, F, across the front end to provide an active volume between B and F, where the primary ions undergo gas amplification. A somewhat heavier metal window at W seals the counter. Potentials of the order of 2,000 v may be required in the operation of this counter. Therefore, it is advisable to include a grounded guard ring, G_1, which protects the central electrode from leakage pulses from the cathode. Counters of this type are usually used in experiments where it is not necessary to have them permanently filled and sealed.

VII. Preparation and Filling of Geiger-Müller Counters

Considerable diversity of opinion exists regarding various details of the preparation of the electrodes of counters. Many procedures have been proposed that are unnecessary in the preparation of good counters. A few precautions must be observed if a counter is to maintain its characteristics over a reasonable period. Among these are the following. (1) All interior surfaces must be clean in the usual sense of being free of dust, grease, or other extraneous substances. If these parts are carefully rinsed in acetone or similar solvent just prior to assembly there is no necessity for baking the counter out on a diffusion pump before filling; (2) the interior surfaces, including that of the center wire, should be smooth and well polished for best results; (3) the counter should be flushed with the filling gas several times before the final filling. With these precautions a thoroughly vacuum-tight counter will have a useful life determined by the number of counts that can pass through it without altering the nature of the filling mixture. It can also be expected to have a plateau with a slope of 2 to 3 percent per hundred volts over a range of at least 150 v.

A great variety of metals may be used for the electrodes. The center wires are frequently of polished steel or tungsten, but other metals will function equally well if they are not corroded by the filling mixture. Some authors recommended that the center wires be glowed by passing an electric current through the wire while the counter is evacuated, prior to filling. If the center wire is smooth, this procedure is unnecessary and in many forms of counters it is impossible to arrange for this procedure.

1. Filling Procedure

For counters that are made largely of metal or have heavy metal electrodes, a very simple filling system is adequate. No diffusion pump is required, since very little gas can be removed from metals at temperatures that the various soldered joints in metal counters will withstand. There is very little evidence that prolonged pumping with diffusion pumps improves the properties of a counter, in any case. Most counters made at present are of the self-quenching type, so that provision must be made to introduce an organic vapor and a noble gas, usually argon, into the counter. The necessary parts to accomplish this are shown in the diagram in figure 36. Various procedures for obtaining the correct ratio of vapor to gas in counters have been made. A satisfactory procedure, using the system shown in figure 37, is to evacuate all parts of the system, closing the stopcock on the organic liquid reservoir as soon as the air has been expelled. The stopcock on the liquid reservoir is then closed. Barring accidents this bulb need not be evacuated again. Evacuation is continued until an apparent vacuum is obtained, with the stopcocks open to the counter. The system exclusive of the vapor reservoir is then flushed with argon from the cylinder by admitting the gas to about atmospheric pressure, as observed on the pressure gauge, closing the cylinder valve and reevacuating. A pressure gauge reading −30 to +30 in. Hg pressure is convenient for this purpose. The system including the counter is again filled to atmospheric pressure with gas from the cylinder and the stopcock to the gas reservoir closed. The gas in this reservoir is used for filling and flushing counters. Now the system exclusive of the reservoir is evacuated, the stopcock to the pump closed, and organic vapor admitted to the counter to a pressure of several centimeters as read on the mercury manometer. In many cases this will be the total vapor pressure of the liquid. The stopcock to the liquid reservoir is then closed and time allowed for the vapor pressure to become constant. Then the vapor is pumped down to the pressure desired for filling the counter. This will usually be between 1 and 2 cm on the mercury manometer, since a ratio of 1:10 of vapor to gas usually gives best results. The stopcock to the pump is closed and gas admitted from the gas reservoir until the total pressure is

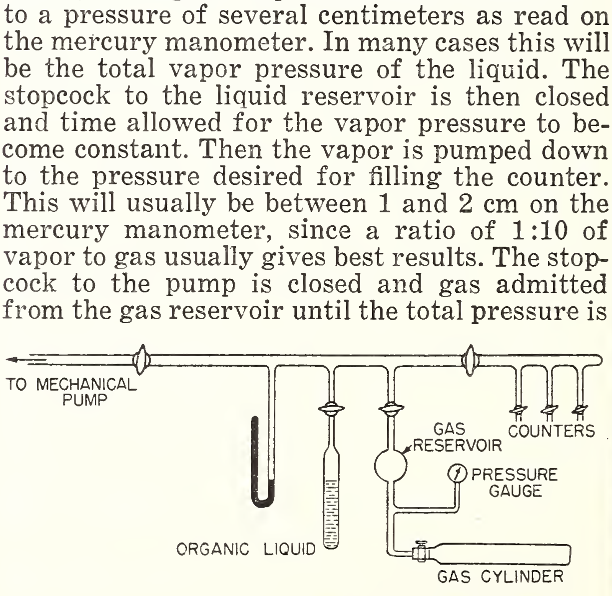

FIGURE 37. *A typical system for filling counters.*

at the desired value, usually from 8 to 15 cm. The stopcocks on the individual counters may now be closed and several hours allowed for the gas mixture to come into equilibrium. The counters should be tested for starting voltage and plateau before they are sealed off. This allows them to be refilled if the first filling did not give the desired characteristics. Although many organic vapors have been tried successfully, such as amyl acetate, ether, and pentane, in self-quenching Geiger-Müller counters, alcohol is generally most satisfactory for the laboratory worker who prepares his own counters.

In use, counters should be protected from exposure to light and from excessive variations in temperatures. Changes of temperature affect the starting voltage and may alter the shape of the plateau. Individual counters vary considerably in this respect. For an alcohol-argon mixture fluctuations in temperature of a few degrees produce no serious changes in operating characteristics if the counter has a fairly level plateau over a range of 150 v and is operated near the middle of the plateau.

VIII. Bibliography

For the benefit of those readers who desire to pursue the study of the construction and use of counters in greater detail than could be included in this Circular, a list of titles and authors is given below. This list is not exhaustive but includes typical papers under each heading that will serve to introduce the reader to the literature on these various topics.

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