Geiger Counter Tubes*

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Summary—**The following are some of the many processes that contribute to the mechanism of the discharge in Geiger counters: formation of the primary ion pairs; ion multiplication within the gas by Townsend avalanche formation; spreading of the avalanches through photoelectric absorption of ultraviolet quanta in the gas; transfer of ionization energy from positive ions of the rare gases to the polyatomic molecules of the "quenching" admixture; release of secondary electrons at the cathode by positive ions and metastable atoms; de-excitation of metastable atoms of the rare gases by collisions with atoms of admixed foreign gases; and decomposition of polyatomic molecules by electron impacts and photon absorption. Present theories provide a qualitative understanding of the fundamental roles played by all of these processes, but their combined effects are too complex to predict the wide variation in characteristics of tubes obtained with slightly altered practices of construction or choices of gases. This paper is a review of existing theories and methods of constructing tubes to obtain maximum counting efficiencies and other desirable characteristics, such as low threshold voltage, thermal insensitivity, long life, high resolution, and low background.**

SINCE THE FIRST demonstration of the tube counter by Geiger and Muller in July 1928,[1] the unusual sensitivity of such counters has found widespread applications in the detection of high-speed particles and energetic photons. The extensive literature on Geiger counters is not only indicative of their manifold uses, but is also a measure of the divergence of theories devised to explain their mechanism and the numerous recipes prescribed for the preparation of good counters. In the last ten years, however, a consistent and relatively complete theory of counter-tube operation has been developing,[2-8] together with a know-how for their construction, which now permits production of large numbers of reliable tubes with identical characteristics. This paper is a review of current theories of the mechanism of the Geiger-counter discharge and a survey of the many different types of counters designed for specialized applications.

A Geiger counter is a gas-filled diode operated in the region of the unstable corona discharge. There are two types of counters, characterized by their filling gases. One uses simple monatomic or diatomic gases, such as hydrogen, air, the rare gases, or mixtures of these, and is known as the nonself-quenching type. The second category includes mixtures of simple gases and small percentages of "quenching" admixtures, which are usually polyatomic organic molecules. In general, the firing characteristics of both types of fillings are very much alike, but the subsequent stages of the discharge and the deionization processes are distinctly different. The emphasis in this paper will be devoted almost entirely to a description of the self-quenching type of tube, which is now used almost universally in preference to the simple gas type. The condition for starting a discharge is that at least one low-energy electron be produced within the counter gas. This electron kindles an avalanche discharge which spreads rapidly throughout the length of the tube and lasts for a few microseconds. Within a fraction of a millisecond after the triggering event, all ions and electrons are cleared out of the interelectrode space, and the tube is ready to respond again to the passage of another ionizing particle. A single electron is capable of triggering a discharge which can be easily detected with little or no amplification. In this respect, the Geiger counter comes close to fulfilling the requirements of a perfect detector.

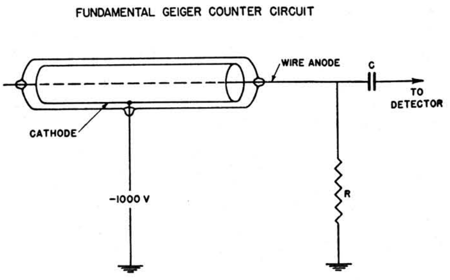

Fig. 1—Fundamental Geiger-tube circuit.

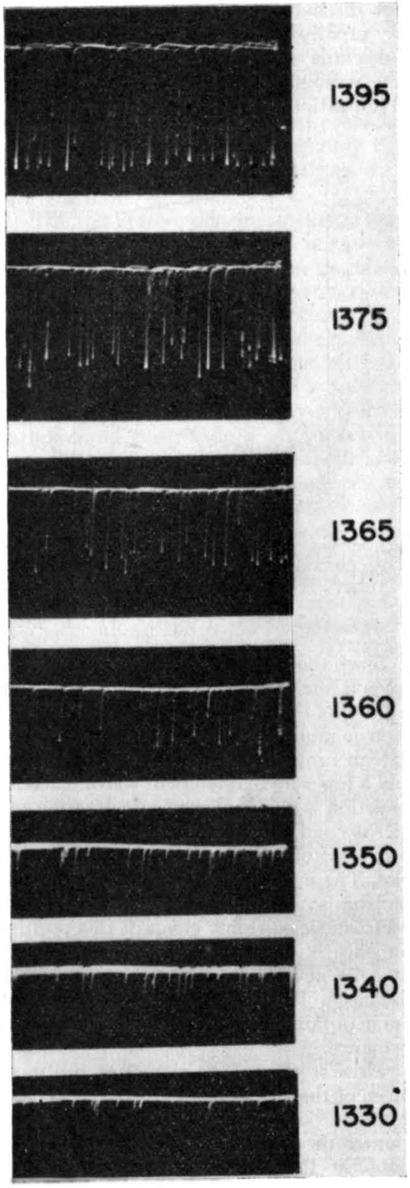

Fig. 2—Approach to uniform pulse amplitudes near Geiger-counting threshold. Counter-tube dimensions are 10, 1.0, and 0.0125 cm. Argon-ammonia filling.

The electrode system of a Geiger counter usually consists of a fine wire and coaxial cylinder. Most tubes are filled with a rare gas combined with a trace of a polyatomic vapor such as alcohol, ether, amyl acetate, and many others. At low voltages, the tube behaves as an ionization chamber with an internal amplification factor of unity. A relatively small potential difference prevents recombination losses, and is sufficient to draw a saturation current from the tube, supplied entirely by the primary ionization. Raising the voltage brings on gas multiplication by impact ionization of the gas molecules in the manner of the familiar Townsend avalanche. The multiplication factor increases with increase in voltage, and the current delivered by the tube is proportional to the primary ionization up to multiplications of 10^5 or 10^6. Throughout this range, the discharges are single Townsend avalanches, each avalanche originating from a primary ion pair and localized within a fraction of a millimeter along the length of the wire. At still higher voltages, every avalanche breeds new avalanches, spreading the discharge along the full length of the tube, through the medium of the very-short-wavelength ultraviolet rays generated in each Townsend avalanche. The discharge continues to burn until a critical space-charge density of positive ions is reached. The amplification factor then becomes independent of the amount of primary ionization, and all discharge pulses attain equal amplitudes. This condition characterizes the operation of the Geiger counter. The Geiger-counting threshold is usually determined experimentally by observing, with an oscilloscope cou-

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[1] H. Geiger and W. Muller, "Technical considerations concerning the electron counting tube," *Phys. Zeit.*, vol. 29, pp. 839–841; November, 1928. Also, vol. 30, pp. 489–493; August, 1929.

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[3] C. G. Montgomery and D. D. Montgomery, "Discharge mechanism of the G-M counter," *Phys. Rev.*, vol. 57, pp. 1030–1040; June, 1940.

[4] W. E. Ramsey, "Measurements of discharge characteristics of G-M counters," *Phys. Rev.*, vol. 57, pp. 1022–1029; June, 1940.

[5] H. G. Stever, "The discharge mechanism of fast G-M counters from the dead time experiment," *Phys. Rev.*, vol. 61, pp. 38–52; January, 1942.

[6] S. A. Korff and R. D. Present, "The role of polyatomic gases in fast counters," *Phys. Rev.*, vol. 65, pp. 274–282; May, 1944.

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[8] A. G. M. Van Gemert, H. Den Hartog, and F. A. Muller, "Measurements on self-quenching G-M counters," Parts I and II, *Physica*, vol. 9, pp. 556–564 and 658–664; June and July, 1942.

pled to the simple circuit of Fig. 1, the lowest voltage at which all pulses become equal in size. As threshold is approached, statistical fluctuations in the breeding of new avalanches from preceding avalanches may interrupt the chain before the discharge has filled the entire length of the tube. The transition to Geiger counting is ordinarily very sharply defined, as is illustrated in Fig. 2, which shows the rapid transition from incomplete growth of the discharge characterized by nonuniform pulse heights, to the threshold where each discharge has spread throughout the tube. The number of discharges is directly related to the number of primary particles striking the tube, and does not depend appreciably on the applied potential over a range of a few hundred volts known as the "plateau." At higher voltages, the condition of a self-sustained corona is reached, and the discharge maintains itself until the potential is removed. Sufficiently high potentials bring on the transition to a glow discharge in which the current rises very rapidly and the voltage across the electrodes falls to a low stable value. The complete voltage characteristic of the cylindrical ionization tube is illustrated in Fig. 3.

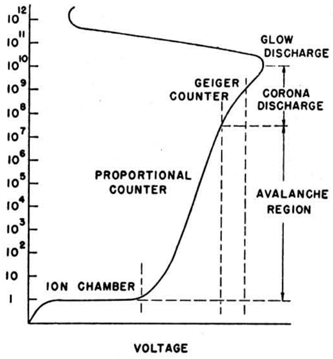

Fig. 3—Gas amplification versus voltage in a coaxial-cylinder type of ionization tube.

Since the gradient of the electric field between a fine wire and a cylinder is very high in the immediate neighborhood of the wire, electron multiplication in the Geiger-counter plateau range is confined to a narrow zone only a few wire diameters in width. Electron collection is accomplished in a fraction of a microsecond, during which the positive ions form a virtually stationary sheath about the wire. The eventual severing of the chain of electron avalanches is attributable to the electrostatic shielding effect of this positive-ion sheath. Subsequently, the ion sheath must be neutralized without reigniting the discharge. This constitutes the major problem in obtaining successful counter-tube performance.

At first glance, the structure and mechanism of the Geiger counter appear to be deceptively simple. The complete Geiger-counter mechanism is rather complex and involves (1) the Townsend avalanche, (2) the spreading of the discharge, (3) the motion of the ion sheath and growth of the pulse, (4) the deionization process, and (5) all the effects involved in suppression of spurious pulses. This last category includes ionization transfer from positive ions of the rare gas to polyatomic vapor molecules, suppression of secondary emission at the cathode, quenching of metastable states, and photodecomposition of the polyatomic gas.

The performance of any particular Geiger counter is described by its threshold voltage, the length and slope of its plateau, its efficiency, pulse characteristics, maximum counting rate, temperature dependence, and useful life. No single type of counter exhibits all of the ideal characteristics, but some tubes meet the requirements of specialized applications almost to perfection.

THE TOWNSEND AVALANCHE

The electric field strength between coaxial cylinders is given by

$$E(r) = \frac{V}{r \log \frac{b}{a}} \qquad (1)$$

where $E(r)$ is the field at distance r from the axis, V is the applied potential difference, and b and a are the cathode and anode radii, respectively. Consider a typical counter, operating with an applied potential difference of 1,000 volts. The field strength at the surface of the wire is about 40,000 volts per cm. It falls inversely as the distance from the wire and is less than a few hundred volts per centimeter at distances greater than $b/2$ from the anode. Immediately after the passage of an ionizing particle, the secondary electrons which it produced are accelerated radially toward the wire. Each electron gains energy, which it loses through inelastic collisions leading to excitation or ionization of the gas. Every inelastic collision brings the electron to rest, after which it starts to travel its next free path in the direction of the field. The excited molecules may radiate their energy or be de-excited by subsequent collisions. If, for example, the counter is filled with hydrogen to a pressure of 100 mm Hg, the electron mean free path is about 10^{-3} cm, and sufficient energy for impact ionization cannot be gained in one mean free path until the electron reaches the high-field region very close to the wire. The potential fall per mean free path at the cathode is as little as 0.2 volts, but rises to about 20 volts at the surface of the wire. This energy gained per mean free path first reaches the ionization potential of the hydrogen molecule, 16 ev, at a distance of four free paths, which is slightly less than one wire radius from the surface of the wire. Beyond the immediate neighborhood of the wire, the energy for ionization can be acquired only over several mean free paths.

Increasing the voltage across the counter toward the threshold for Geiger counting expands the multiplication zone in the gas over an increasing number of mean free paths. More and more electrons are added to the avalanche, together with photons radiated from excited states of higher energy which are capable of photoionizing the gas or photoelectrically releasing electrons from the cathode. These photoelectrons are in turn accelerated toward the wire, where they contribute new avalanches. Geiger-counting threshold is marked by the release of a sufficient number of photons per avalanche to guarantee the generation of a succeeding avalanche by photoelectric effect in the gas or at the cathode.

The properties of the single Townsend avalanche can generally be summarized as follows: At threshold the multiplication factor in the avalanche is about 10^5; each avalanche is quite discrete, and the lateral extension along the length of the wire arising from diffusion of the electrons in the avalanche is about 0.1 mm; the duration of the single avalanche is less than 10^{-9} second measured from the beginning of the multiplication process.

The threshold voltage for the corona discharge depends for the most part on the nature of the gas as characterized by the first Townsend coefficient η, which is defined as the ionization produced by an electron per volt of potential difference. The coefficient η depends on the energy gained by an electron per mean free path, which is a function of the ratio of field strength E to pressure p. The threshold requirement that each avalanche release a sufficient number of quanta to photoelectrically trigger another avalanche is expressed in terms of a second coefficient, γ, as

$$\gamma n = 1 \qquad (2)$$

where γ is the number of photoelectrons ejected per ion pair formed in the gas and n is the number of ion pairs per Townsend avalanche. Experimentally, it is observed that γ for the simple gases does not vary markedly with different cathode materials, but that the nature of the gas, its pressure, and the electrode geometry, as reflected in η, are the quantities which are mainly responsible for establishing the threshold voltage.

Among the diatomic and inert gases, equal values of η are achieved at widely different values of E/p. The rare gases—helium, neon, argon, krypton, and xenon—produce higher threshold voltages in the order of increasing atomic number. Hydrogen requires a higher starting voltage than argon, and that of air or nitrogen is still higher. Traces of impurities have a pronounced effect on the starting voltage of the corona, as will be shown in a later section. Most present-day counter tubes include a small percentage of a polyatomic "quenching" gas in addition to the rare gas which is usually the major constituent. Although the ionization potential of this polyatomic constituent is always lower than that of the rare gas, its presence almost invaraibly raises the threshold voltage. This is so, because a large portion of the electron energy is dissipated in exciting molecular vibrations at each impact, rather than ionizing. Polyatomic molecules with absorption bands in the near infrared portion of the spectrum can absorb energies amounting to a fraction of an electron volt, or less than the energy acquired by an electron per mean free path even in the neighborhood of the cathode. Inelastic collisions can, therefore, bring the electron to rest every time it encounters a polyatomic molecule. In contrast to the simple gas fillings, an electron is much less likely then to acquire ionization energy over several free paths. As a result, the zone of ionization contracts with addition of the polyatomic gas, and the minimum field strength for a corona discharge increases. Argon with alcohol admixture is one of the most commonly used

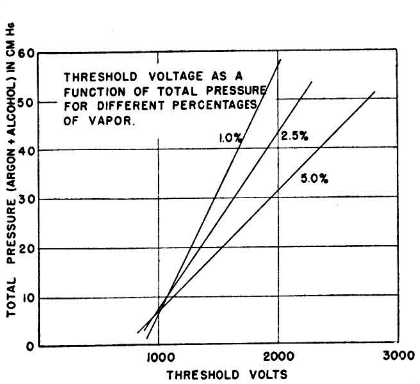

Fig. 4—Variation of threshold voltage with composition and pressure of a self-quenching gas mixture. (After Trost in footnote reference 2.)

Geiger-counter fillings. Fig. 4 illustrates the effect of argon pressure, percentage of alcohol admixture, and the size of the electrodes on the threshold voltage.

Spread of the Discharge and Formation of the Ion Sheath

Above the threshold of Geiger counting, thousands of Townsend avalanches per centimeter of length of the tube are ignited through the emission and absorption of ultraviolet light. Neutral gas molecules are excited by electron impacts in the avalanche process and, in returning to the ground state, emit ultraviolet quanta with energies below the ionization potential of the gas. If the counter tube is filled with simple gases, the ultraviolet photons generate new avalanches by releasing photoelectrons at the cathode. The rate of spread of the discharge is then dependent only on the lifetime of excited atoms or molecules and on the photon transit time.

If a polyatomic vapor admixture such as alcohol is included with the simple gas, the photon mechanism is very much altered. In a mixture of argon and alcohol, the highest excited states of argon at about 11.6 ev exceed the energy required to ionize an alcohol molecule, 11.3 ev. Energetically, therefore, it is possible for the ultraviolet photon radiated by an argon atom to ionize a molecule of alcohol, and thereby release an electron which may trigger a new avalanche. The efficiency of such absorption processes is so great that the number of quanta arriving at the cathode is insufficient to provide any significant number of photoelectrons. In addition to the absorption of ultraviolet quanta by the polyatomic gas, there is evidence for absorption processes in the rare gas itself, although their mechanism at present is not well understood.

Many investigations have been attempted with the object of identifying the nature of the ultraviolet radiation and its modes of production and absorption within the gas mixtures used in counters. Among the earliest of these experiments was that of Greiner,[9] who studied counters filled with oxygen, hydrogen, or air. The experiment consisted of mounting two counters inside the same envelope, with their cylinders open to each other and their anodes separated by about 1 centimeter. From measurements of the number of counts which spread from one counter to the other at different pressures, Greiner computed absorption coefficients for the different gases. To prove that the spreading was accomplished by the passage of ultraviolet radiation across the gap between the counters, he inserted light filters between the tubes. Only the thinnest nitrocellulose films, about twenty-thousandths of a micron in thickness, which were transparent to ultraviolet radiation below 1,000 Å, permitted the discharge to spread from one tube to the other.

Greiner's experiment was performed with simple gases, in which the ultraviolet radiation regenerated Townsend avalanches by a cathode photoelectric effect. In another version of this type of experiment, Ramsey[10] showed that two counters would trigger each other in coincidence when filled with monatomic or diatomic gases, but that the introduction of a small amount of polyatomic admixture caused the counters to fire at random with respect to each other. Furthermore, by plotting coincidence rate versus resolving time of the coincidence circuit, it was found that the photoemission was confined to a period of approximately 1 microsecond, even though the pulse on the counter wire required from 1 to 20 microseconds to attain one-half its peak amplitude.

The mean free path of the ultraviolet radiation responsible for spreading the discharge in counters with polyatomic constituents has been evaluated by a number of experimenters. Stever[4] obtained an interesting picture of the process by using divided cathodes and beaded anodes. In the latter type of counter, glass beads were sealed on to the wire at equal intervals along its length. From observations of pulse size, it was established that the discharge jumped the obstacle of the glass bead only if the beads had less than a minimum diameter, or what is equivalent, if the ratio of field strength to pressure E/p exceeded a critical value. Further[11] studies showed that, besides the obstructing effect of the glass bead for ultraviolet light, the field intensity was reduced about the glass bead. The photons were all absorbed in the immediate neighborhood of the bead where the field was too low to develop a complete avalanche.

Attempts to clarify the details of the emission and absorption processes have not been entirely successful. Alder[12] and his coworkers recently performed a variation of the Greiner type of split-counter experiment to determine the absorption coefficient of an alcohol vapor admixture for the ultraviolet photons emitted in the discharge. The two counters were mounted in a common envelope at a fixed separation of 11 centimeters. At first, the counters were filled with a mixture of simple gases, argon plus air, which gave satisfactory counting characteristics. With this filling, every count in one tube triggered the companion tube coincidentally. Contaminating the simple gas mixture with only a few tenths of a millimeter Hg of alcohol sufficed to reduce the number of spreading discharges to a vanishingly small figure. The absorption coefficient computed from this experiment was 640 cm^{-1} (at atmospheric pressure). With an admixture of 15 mm Hg of alcohol, the number of photons fell to $1/e$ of its initial value in 0.8 mm. In obtaining this result it was assumed that introducing alcohol in these low concentrations did not affect the number of photons per discharge nearly so much as it did the absorption of photons.

Still another experiment of this type, reported by Liebson,[13] attempted to avoid the possibility of confusing a decrease in photon emission with an increase in absorption coefficient. All conditions of the discharge were held constant and only the gas path which the photons were required to traverse was altered, by an expanding bellows connection between the counters. The magnitudes of the total absorption coefficients for the rare gases, with the alcohol or methylene bromide admixtures which he used, were comparable to those computed by Alder and his coworkers, but Liebson found that constant coefficients per unit pressure were obtained only if the absorption were attributed entirely to the rare gas.

The qualitative conclusion to be drawn from these experiments is that, in gases containing polyatomic admixtures, the absorption of ultraviolet quanta by photoionization of the gas is very effective in confining the spreading mechanism to the immediate neighborhood of the wire. The ultraviolet radiation may be composed of a number of wavelengths, some of which may reach the cathode and contribute a photoelectric effect. Experiments with split-cathode counters,[14,15] filled with the typical operating mixtures, showed a small but measurable spreading of the discharge by ultraviolet radiation absorbed in the gas at distances of many centimeters, which could not be attributed to the same photons which propagate the discharge along the wire. These less-abundant photons were also capable of ejecting an appreciable number of cathode photoelectrons as part of the mechanism of spreading the discharge. In any combination of gas mixtures and cathode surfaces, it may be expected that all of these processes of photon emission and absorption in the gas and photoelectric emission at the cathode play a role, but their relative importance may differ considerably. There is a need for still more refined measurements of the production of photons and the cross sections of photon absorption between 600 Å and 1,200 Å before the Geiger-counter mechanism can be quantitatively described.

If Alder's value of about 1 millimeter for the mean free path of the quanta is accepted, it is immediately apparent that the dis-

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[9] E. Greiner, "On the spreading of the discharge in counter tubes," *Zeit. Phys.*, vol. 81, pp. 543–555; March, 1933.

[10] W. E. Ramsey, "Period of photon emission in a counter discharge," *Phys. Rev.*, vol. 58, pp. 476–477; September 1, 1940.

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[13] S. H. Liebson, "The discharge mechanism of self-quenching G-M counters," *Phys. Rev.*, vol. 72, pp. 602–608; October, 1947.

[14] J. D. Craggs and A. A. Jaffe, "Discharge spread in Geiger counters," *Phys. Rev.*, vol. 72, pp. 784–792; November, 1947.

[15] C. Balakrishnan, J. D. Craggs, and A. A. Jaffe, "Discharge spread in Geiger counters with methane and methane-argon fillings," *Phys. Rev.*, vol. 74, pp. 410–414; August, 1948.

charge in a counter with a polyatomic admixture will spread with a smaller velocity than in a simple gas counter. The original avalanche will radiate quanta in all directions and breed new avalanches, whose number will fall exponentially with distance from the parent avalanche. The first generation of avalanches will initiate succeeding generations and the discharge will spread step-wise along the length of the wire, producing thousands of avalanches per centimeter. Since the duration of a single step can not be much less than 10^{-8} second, the velocity of spread may be as slow as 10^6 to 10^7 centimeters per second.

The relation between the velocity of spread and the overvoltage is almost linear.[16] By lowering the noble-gas pressure without altering the quenching-gas pressure, the spread velocity is increased. This behavior could be explained by a decrease in the duration of a single avalanche because of increased electron mobility in the avalanche. The velocity of propagation furthermore depends on the nature of the noble gas, all other factors being constant. For example, the discharge spreads about three times as fast in helium as in argon. Here, again, the explanation may be in the higher electron mobility in helium compared to argon, which would be expected to decrease the duration of the individual avalanche.

Growth of the Pulse

Because of the enormously greater mobility of the electrons compared to the positive ions (about 1,000/1), the positive ions at the wire move only a few thousandths of a centimeter before the completion of the electron avalanche. As the discharge continues, the positive-ion space-charge sheath builds up, until the field strength near the wire is lowered beyond that required to maintain gas multiplication.

For small overvoltages, the charge generated per unit length of counter depends almost linearly on the overvoltage $V-V_s$, which is the difference between operating voltage and threshold. At higher overvoltages the slope of the curve of charge per pulse versus overvoltage falls to about half its initial value. At a given overvoltage the charge per pulse is almost independent of the pressure and depends only on the geometry. These characteristics are illustrated by the curves of Fig. 5 for alcohol-argon mixtures. The capacitance of a typical counter ($=1$ cm, $a=0.01$ cm) supports a charge of about 1.2×10^{-13} coulombs per cm of length per volt of potential difference. In most counters of average size, the charge per pulse lies between 10^{-11} and 10^{-13} coulomb per cm of length at threshold, and may be 100 times as great at the end of the plateau.

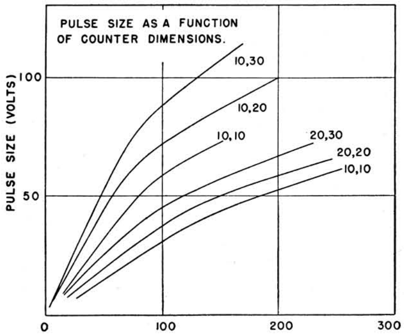

Fig. 5—Dependence of pulse amplitude on counter-tube dimensions and overvoltage. Tube dimensions are indicated as cathode radius (mm), and wire radius (thousandths of a cm). (After Trost in footnote reference 2.)

The voltage pulse on the wire can be attributed entirely to the motion of the positive ions. The electrons are held on the wire by the image force field of the positive ions. Initially, with the sheath almost in contact with the wire, nearly all the electrons are bound to the wire. As the sheath expands radially, the image charge decreases and the electrons flow away from the anode, giving rise to a voltage pulse on the grid of the amplifier coupled to the wire of the counter. The rate of release of electrons at the wire depends on the rate of drift of the ion sheath, which, in turn, varies with the radius of the sheath. The radial velocity of the sheath is approximately proportional to the field or inversely proportional to the radial distance from the wire. At the start, the shape of the pulse is affected by the time required to propagate the discharge throughout the length of the tube. Since the discharge may spread at the rate of about 10 cm per microsecond in a self-quenched counter, it may require of the order of a microsecond for the entire ion sheath to mature in a long counter, during which time the voltage pulse can rise to a few tenths of its peak value (without differentiation). The rate of rise increases until the time at which the ion sheath is completed. After the sheath is completed, the rate of rise of the pulse decreases. It may attain one-half its peak value in 1 or 2 microseconds, and thereafter increase very slowly. With infinite series resistance in the fundamental circuit (no *RC* differentiation), the pulse would reach its final and maximum value in the time required for the positive-ion sheath to traverse the tube, about 10^{-4} to 10^{-3} second. Decreasing the series resistance allows the applied potential to be restored on the wire in accordance with the time constant given by the product of the wire system capacitance and the series resistance. The appearance of the differentiated pulse for different values of the series resistance is shown in Fig. 6.

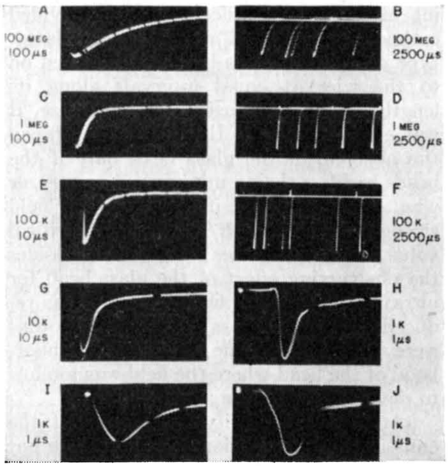

Fig. 6—Effect of series resistance on pulse shape. The counter tube had the dimensions 10, 1.0, 0.0125 cm, and a capacitance of a few micromicrofarads. The series resistance *R* was varied to alter the *RC* constant of the fundamental circuit, Fig. 1. Strips *A* to *H* were taken with an argon-CH_2Br_2 mixture in the counter. The time markers on each trace are identified alongside each strip. Traces *B*, *D*, and *F* were photographed with a recurrent sweep. All of the others are triggered sweep patterns. Strips *I* and *J* illustrate the effect of overvoltage on the rise time of the pulse in a neon-argon-chlorine mixture with a threshold of 550 volts. Trace *I* was taken at an overvoltage of 50 volts, trace *J* at 300 volts. All photographs were made with a DuMont Type 248 oscilloscope.

The Dead Time and Recovery Time

As the positive-ion sheath moves outward towards the cathode, the field near the wire returns to normal. The time required for the positive ions to reach the critical distance from the wire corresponding to threshold field defines the dead time of the counter. During this period the counter is insensitive to the passage of further ionizing particles. The additional time required for the ions to reach the cathode is called the "recovery time," and the size of any pulse occurring within this time is determined by the time elapsed since the initial discharge, a pulse at the end of the recovery time being of the same size as the initial pulse.

Figs. 7(a) and 7(b) show a triggered sweep pattern of the type first used by Stever[5] to illustrate the dead-time and recovery-time characteristics for a self-quenching tube. Following the trigger pulse, the sweep shows no pulses until the dead-time interval is passed, at which time small pulses begin to appear. These grow in amplitude with elapsed time from the triggering of the sweep. The envelope of these pulses traces the shape of the recovery curve of the electric field near the anode wire, as shown in Fig. 7(c). From studies of the recovery curve, it is possible to obtain considerable information about ion mobilities in different gases and at various field strengths. Many interesting observations have already been made. For example, it is possible to identify the ions making up the sheath in mixtures of polyatomic gases, such as, for example, alcohol and methane, where the recovery time was found to be characteristic of the drift time of alcohol ions.[17] In many gases the observed mobilities are identified with fragment ions, rather than the parent molecules.[18] The drift time of the ions in a hydro-

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[16] J. M. Hill and J. V. Dunworth, "Rate of spread of discharge along the wire of a Geiger counter," *Nature*, vol. 158, pp. 833–834; December 7, 1946.

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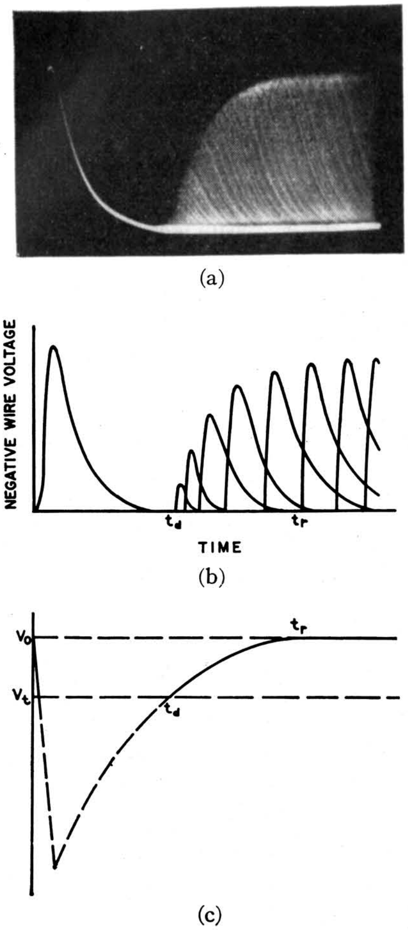

Fig. 7—(a) Dead-time pattern photographed on triggered sweep.
(b) Schematic representation of a dead-time pattern, indicating dead time t_d at the foot of the envelope of pulses triggered during the recovery interval from t_d to t_r.
(c) Variation of electric field at the anode surface during the period of ion-sheath transport from anode to cathode.

gen-alcohol mixture, surprisingly enough, was found to be longer than in oxygen-alcohol, indicating that the mobilities of these ions in the high fields of counters may be considerably different from those measured at small field strengths.[17]

The dead time and recovery time in a tube of ordinary dimensions are roughly equal to each other, and of the order of a few hundred microseconds. The critical distance to which the ions must move before the field at the wire recovers to threshold is about half the counter radius. This critical radius r_c is related to the overvoltage $V-V_s$, the cylinder radius b, and the charge q, per unit length of the ion sheath by

$$r_c = be^{-V-V_s/2q}. \qquad (3)$$

The dead time therefore decreases with increasing overvoltage, and is shorter in a tube of smaller dimensions and larger ratio of anode to cathode diameter. Dead times as short as 5 microseconds have been obtained in tubes having cathode and anode diameters of 0.25 inch and 0.15 inch, respectively.

THE ROLE OF THE QUENCHING ADMIXTURE

The treatment of the Geiger-counter mechanism up to this point provides a picture of the growth of the discharge and the shape of the pulse. Upon the subsequent arrival of the positive-ion sheath at the cathode, the electric field within the counter tube is fully restored. This introduces the possibility of rekindling the discharge by secondary electron emission. Suppose, for example, that the sheath consists of argon ions whose ionization potential is in excess of twice the work function of the cathode surface. An argon ion can first draw an electron out of the cathode and become neutralized. The energy difference between the ionized argon and the work function appears as recombination radiation with an energy in excess of the photoelectric threshold energy. The recombination photon can then eject an electron from the cathode and initiate a new avalanche. In a nonself-quenching counter it is, therefore, necessary to quench the discharge by the use of either a large series resistance or an electronic quenching circuit, which prevents recovery of the threshold counting field until deionization of the gas is complete.

Self-quenching counters are usually produced by admixing a small amount of polyatomic organic vapor to the nonself-quenching gas. Almost any molecule, inorganic as well as organic, containing three or more atoms, will contribute the quenching mechanism. Self-quenched counters have been made with triatomic gases, such as sulphur dioxide and nitrous oxide. Among the diatomic molecules, only the halogens have been found to quench properly. The primary requirement for quenching is that no excited or ionized molecules capable of inducing secondary emission shall reach the cathode surface. In a typical mixture of ten parts of argon to one of alcohol at a total pressure of 10 cm Hg, an argon ion formed in the discharge must make about 10^5 collisions with gas molecules in traversing the anode-to-cathode distance. Because of this large number of collisions, the chances are very favorable for the transfer of ionization from argon ions to molecules of alcohol.[19] Energetically, all that is required is that the ionization potential of the quenching gas be lower than that of argon. This condition is fulfilled by alcohol in argon, and is satisfied by almost all polyatomic molecules in combination with helium, neon, or argon. The ionization potential usually decreases with increasing complexity of the molecule. In the experience of this laboratory alone, over thirty different admixtures were investigated which produced usable self-quenching counters. When krypton or xenon are the vehicular gases, their ionization potentials are lower than those of many of the commonly used quenching gases, and it becomes much more difficult to select admixtures which satisfy the requirements of the transfer process.

In transferring ionization energy to the polyatomic molecule, the neutralized argon ion emits recombination radiation. This radiation may be absorbed by another polyatomic molecule, which then photodissociates into two or more neutral molecules or radicals, with emission of still-longer-wavelength photons. The degradation of the original photon through many processes of this type amounts to a "red shift" of the photon spectrum beyond the photoelectric threshold of the cathode. The positive ions of the polyatomic molecules and dissociation fragment ions migrate to the cathode, where they are neutralized by drawing electrons out of the metal surface. After neutralization, the molecule is left in an excited state from which it may radiate a photon or predissociate without radiating. Radiation is very unlikely to occur because the lifetime against radiation is about 10^{-8} second, which is much greater than the time required for the neutralized atom to travel the remaining distance to the cathode. The quenching process can be completed successfully, then, if (1) the excitation energy left with the neutralized molecule is less than the photoelectric threshold of the cathode, in which case no secondary electrons can be ejected, or (2) the excitation energy is dissipated in predissociation before the molecule collides with the metal wall.

It is possible that the first process, which requires the ionization energy E_i of the quenching admixture to be less than twice the work function ϕ of the metal cathode, may be largely responsible for the excellent quenching properties of the halogens, and perhaps the halogenated hydrocarbons, such as methylene bromide. In experiments conducted here, tubes filled with these admixtures were equipped with quartz windows but produced no photocathode response to the shortest U.V. transmitted by quartz, about 1,850 Å or 6.5 ev. The cathodes used in these tubes were iron or copper, which in vacuum photocells are known to have work functions of 4 to 5 ev. However, it is also well known that in the presence of even the less active gases, the photoelectric threshold of these metals may be considerably shifted, so that it would not be surprising if the halogens were capable of increasing the threshold energies well beyond the limit of 6.5 ev observed in the quartz window tubes. Since E_i of Cl_2 is 13.2 ev and of Br_2 is 12.8 ev, it is apparent that the condition for secondary emission, $E_i > 2\theta$, is not fulfilled.

The second process, in which the molecule predissociates before radiating, becomes more and more probable, the greater the complexity of the polyatomic molecule. Neutralization of a polyatomic ion occurs by field emission[20] which is effective at a distance of about 10^{-7} cm from a metal surface whose work function is about 4 or 5 ev. After neutralization, the excited molecule ($E_{\text{exc}} = E_i - \phi$) must approach within about 10^{-8} cm, of the surface before secondary electron emission is possible.[21] At the thermal velocities with which the positive ions approach the cathode, 10^{-7} cm is traversed in about 10^{-12} second. To avoid secondary emission, the molecule must predissociate in less than

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[19] H. Kallmann and B. Rosen, "Elementary processes in collisions of ions and electrons," *Zeit. für Phys.*, vol. 61, pp. 61–86; March, 1930.

[20] M. L. E. Oliphant and P. B. Moon, "The liberation of electrons from metal surfaces by positive ions," *Proc. Roy. Soc. A.*, vol. 127; pp. 386 et seq; 1930.

[21] H. S. W. Massey, "The theory of the extraction of electrons from metals by positive ions and metastable atoms," *Proc. Comb. Phil. Soc.*, vol. 26, pp. 386–401, part III; 1930.

10^{-12} second. The lifetime against predissociation in polyatomic molecules is closer to 10^{-13} second, about the time of one interatomic vibration. Spectroscopically, this property of predissociation in polyatomic molecules can be detected by the appearance of continuous absorption at wavelengths equal to $(E_i - \phi)$. Using alcohol $(E_i = 11.3$ ev) and copper $(\phi = 4.0$ ev) for illustration, the difference $(E_i - \phi)$ is 7.3 ev, which remains with the molecule as excitation energy, equivalent to absorption of a quantum of 1,700 Å wavelength. The alcohol spectrum shows continuous absorption below 2,000 Å accompanied by photodecomposition, indicating that the neutralized but excited molecules should predissociate in about 10^{-13} second and satisfy the quenching requirement.

THE INFLUENCE OF METASTABLE ATOMS

A metastable atom produced in the discharge remains in that state until its energy is radiated or dissipated in a collision of the second kind. If the metastable atom, which is electrically neutral, drifts to the cathode wall, the probability of ejecting an electron there may be as high as 50 per cent. Although the average lifetime of metastable states in neon before radiation is about 10^{-4} second, Paetow[22] found a measurable current caused by metastable atoms in neon persisting for as long as a second after terminating a discharge between parallel plates.

The highly purified rare gases, taken by themselves, are unsuited for use in counters because their metastable states are so readily excited by electron impacts. Ejection of electrons by these metastables, after the positive-ion sheath has spread beyond the critical dead-time radius, reignites the discharge and leads to trains of multiple counts, or continuous discharge. A counter tube filled with rare gas is, therefore, unusable unless a foreign gas is admixed which de-excites the metastable atoms on colliding with them. Hydrogen is effective in quenching the metastable states of argon and neon, and has been used with those rare gases to make permanent gas mixtures for nonself-quenching tubes. The effect of mixing hydrogen with argon or neon on the performance of a counter operated with an external quenching circuit is illustrated by the plateau curves of Fig. 8. Less than 10 per cent of hydrogen in neon does not provide enough collisions between hydrogen atoms and metastable neon atoms to de-excite completely the metastables before they radiate or reach the cathode. Adding more than 10 per cent of H_2 produces a plateau almost as long as is obtained in pure hydrogen. Argon requires a much greater admixture of hydrogen to produce a satisfactory plateau. The ionization energies E_i, and metastable energies E_m, listed in Table I, show that it is energetically possible that metastable neon can be quenched by ionizing hydrogen, but that argon can be quenched only by exciting hydrogen $(E_{exc} = 11.5$ ev).

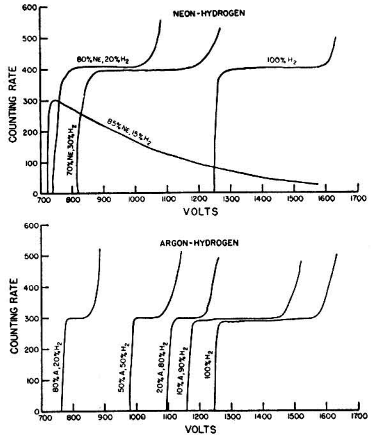

Fig. 8—Plateau curves for mixtures of neon-hydrogen and argon-hydrogen obtained with a Neher-Harper electronic quenching circuit.

Much more striking effects attributable to the quenching of metastable states were discovered by Penning[23] and his coworkers in their studies of breakdown voltages V_B in rare gas discharges. Great differences appeared in the measured V_B which could only be attributed to minute traces of impurities. For example, baking a tube filled with pure neon dropped its V_B by 100 volts, but a subsequent glow-discharge treatment raised it again. A high-frequency electrodeless discharge sometimes raised and sometimes lowered V_B. Only after prolonged glow discharging, which is known to clean up many impurity gases, would V_B reach a stable upper value. By deliberately contaminating neon with traces of argon, mercury, and krypton in concentrations as low as 0.0001 per cent, Pennings obtained remarkable reductions in V_B.

TABLE I

Vehicular gas	Admix. Per cent	E_i	pd	V_B	V_B'
None $E_m = 16.6$ ev	0.02 Kr	13.3	20	350	170
	0.01 H_2	16.1	18	350	260
	0.05 H_2	16.1	18	340	210
	0.01 N_2	16–17	18	350	200
	0.05 N_2	16–17	18	340	160
Argon $E_m = 11.6$ ev	0.03 Kr	13.3	15	500	500
	0.03 Xe	11.5	14	520	530
	0.05 CO_2	15	14	460	470
	0.05 CO_2	14	14	480	500
	0.05 NO	9	14	470	480

NO was the only exception to the rule that V_B is reduced if $E_i < E_m$. Penning suggested that the neutral NO molecule had many states above the ionization limit of 9 volts which were closer to the 11.6 ev of metastable argon, making excitation to those levels more probable than ionization.

It was impossible to explain these results by hypothesizing that, since the admixed gas had a lower ionization potential than the main gas, it was therefore more readily ionized, resulting in a lowering of V_B. The relative contribution of the mercury admixture to ionization, for the case of Hg contamination in neon, was computed to be about 0.0005, entirely too small to be significant. An explanation of the reduced V_B, based on the transfer of excitation energy of neon to ionization energy of the admixture, was more plausible. In pure neon there is no mechanism for converting excitation energy to ionization, but neon atoms excited to metastable states in the discharge could have a relatively great efficiency for ionization of a trace admixture if the energy condition $E_m > E_i$ is fulfilled. Many collisions are made during the life of the metastable atom, and, consequently, the chance of an eventual collision with an admixture atom is great. To materially influence the breakdown voltage, these collisions should occur within a few microseconds of the first avalanche. At the pressures ordinarily used in counter tubes, a metastable atom may make between 10^4 and 10^5 molecular collisions per microsecond. A concentration of quenching admixture as low as 10^{-4} to 10^{-5} would, therefore, effectively remove almost all the metastable atoms within a few microseconds, if every collision between a metastable and an admixture molecule had a high probability of de-exciting the metastable.

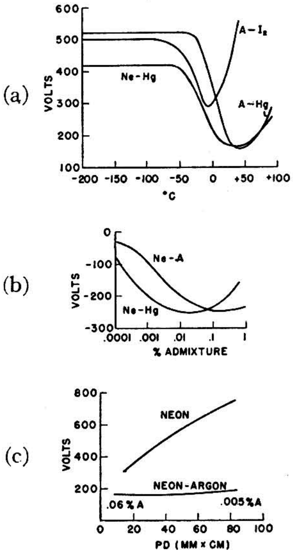

Fig. 9—Effects of impurity gases on the breakdown characteristics of the rare gases. (After Penning in footnote reference 23.) Fig. 9(a) shows the effect of different concentrations of iodine and mercury in argon and neon on the breakdown voltage of the discharge between parallel plates about 1 cm apart. The argon pressure was 15 mm, neon pressure was 21 mm, and the admixture concentration was controlled by its vapor pressure at different temperatures. Fig. 9(b) is a semilogarithmic plot of the Ne-Hg data in percentage of admixture versus decrease in V_B. A similar curve is shown for neon with small percentages of argon admixture. The data of Fig. 9(c) were obtained by starting with 0.06 per cent argon in 10.1 mm of neon, which gave a V_B of 159 volts, and then diluting the mixture with neon up to a maximum pressure of 112 mm, which raised V_B to only 185 volts.

Fig. 9 and Table I summarize the results of Penning and his coworkers. The columns of Table I list: E_i, the ionization potential of the admixture; pd, the product of pressure and distance between electrodes; V_B, the breakdown voltage of the pure rare gas; V_B,

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[22] H. Paetow, "Spontaneous electron emission and field emission following gas discharge bombardment of thin insulating layers," *Zeit. für. Phys.*, vol. 111, pp. 770–790; March, 1939.

[23] F. M. Penning, "The influence of very minute admixtures on the striking voltage of the rare gases," *Zeit. für Phys.*, vol. 46, pp. 335–348; January, 1927.

the breakdown voltage with the admixed impurity gases. The most pronounced effects were obtained with an admixture of argon in neon, where as little as 0.005 per cent argon in 112 mm Hg of neon reduced the striking voltage from 770 volts to 185 volts between parallel plates, 7.5 millimeters apart (Fig. 9(c)).

LOW-VOLTAGE COUNTERS

The condition that E_m of the rare-gas atoms be higher than E_i of the admixture is satisfied by a great many of the polyatomic quenching gases commonly used in counters. The tendency to reduce the striking voltage by converting metastable energy to ionization energy, however, is opposed by the tendency toward inelastic electron impacts with the polyatomic molecules. These impacts keep the electron energies below E_m and E_i of the rare gas and suppress the growth of Townsend avalanches, thereby raising the threshold-voltage requirement. In normal counter mixtures, the concentration of polyatomic constituent needed to quench adequately the discharge and produce a satisfactory life is so high that the process of holding down the distribution of electron energies in the avalanche through inelastic impacts with polyatomic molecules is more important than the ionization of metastables. The most notable exception observed here thus far was methylene bromide in argon, where the amount of admixture could be reduced to a few tenths of a per cent without destroying the quenching properties of the mixture. Such tubes, operating at 250 volts, exhibited plateaus about 100 volts long and had useful lives of 10^7 counts. Weisz[24] observed the effect of diluting hydrocarbon admixtures in argon to very low concentrations. The threshold voltage was markedly reduced in every case satisfying $E_m > E_i$, although no examples were observed which promised practical usefulness in the sense of satisfactory plateaus and long counting life.

Recent attempts to produce low-voltage thresholds in counters, with the neon-argon mixture and others described in Table I above, have been very successful. Previously the lowest operating voltages had been obtained by reducing the gas pressure, decreasing the anode and cathode radii, or introducing a grid. None of these techniques produced low voltage thresholds without sacrificing other desirable features, such as high efficiency and fast recovery times. The theory of operation of counters filled with permanent gases having high threshold voltages and utilizing electronic quenching, applies equally well to mixtures of the Ne-A type with their characteristically low values of V_B. Simpson[25] prepared counters filled with 5 cm Hg of neon and 0.01 per cent argon, which operated in a Neher-Harper quenching circuit with thresholds at 120 to 135 volts. Self-quenching counters having low threshold voltages were prepared by adding fractions of a mm Hg pressure of polyatomic vapors to the neon-argon mixture. At the lowest threshold voltages, obtained by using the minimum amounts of vapor, such counters were temperature-sensitive, short-lived, and required some electronic circuitry to assist the quenching. Using somewhat higher pressures, i.e., 1 mm Hg of ethylacetate and 50 cm Hg of Ne-A fast counters were made in this Laboratory with thresholds of 350 volts and plateaus of 100 to 150 volts. These counters had useful lives of about 10^7 counts.

Counters employing traces of the halogen gases with neon or argon[26] have low threshold voltages combined with many other desirable properties. They cannot be damaged by excessive counting rates or running over the upper voltage limit of the plateau. When chlorine or bromine is used, the tubes are insensitive to temperature variations over a wide range. As was indicated in Penning's experiments, a halogen admixture is also capable of reducing the corona breakdown voltage, when the energetic requirement $E_i > E_m$ is satisfied. Fig. 9 shows that a trace of iodine ($E_i = 9.7$ ev), in argon ($E_m = 11.6$ ev) was as effective in reducing V_B as was Hg. In a similar manner, chlorine ($E_i = 13.8$ ev) and bromine ($E_i = 12.8$ ev) should ionize metastables in neon ($E_m = 15.6$ ev). At higher concentrations of halogen admixture, the halogen acts predominantly as an electron trap and raises the breakdown voltage. As the halogen concentration is reduced, however, ionization of the halogen molecules upon impact with metastable rare gas atoms becomes more probable than electron attachment, and the starting voltage is lowered. Fortunately, relatively small concentrations of halogen are required to satisfy all the Geiger-counter quenching requirements. It has been pointed[27] out that, in theory, the halogens possess the properties required in quenching that are otherwise found only in polyatomic molecules.

A major difficulty in the use of halogen admixtures is the clean-up of the small amount of halogen, originally present, by chemical reactions within the tube. Tubes constructed with electrodes of brass, copper, silver, aquadag, and various plated surfaces failed very quickly when filled with a rare gas plus a halogen admixture. Satisfactory results have thus far been obtained with the use of tantalum and of chrome-iron, and bromine appears to be much less reactive than chlorine. If the efficiency of the counter for ionizing events need not be greater than 90 per cent, higher concentrations of the halogens may be used, and a slow clean-up then produces a correspondingly slower deterioration. Both the inefficiency and operating voltage rise rapidly with increasing halogen admixture, however, and it is much more desirable to seek to eliminate the chemical clean-up process from the beginning, rather than to resort to higher concentrations of the halogen.

The pulse characteristics in low-voltage counters differ only to a minor degree from those of the more common higher-voltage counters. The lower the operating voltage, the longer is the rise time of the pulse. At the lowest voltages, the time to reach peak amplitude may be ten times as long as in similar "high"-voltage counters. The charge per pulse is also considerably greater. Dead times are not appreciably different, and generally center about 200 microseconds for tubes of ordinary dimensions.

THE PLATEAU CHARACTERISTIC AND SPURIOUS COUNTS

The plateau of a Geiger counter may be defined as the voltage range over which the counting rate at a constant intensity of irradiation is substantially independent of voltage. If the term "counting range" is taken to mean the difference in voltage between threshold and the inception of a self-sustained corona discharge, then the plateau is always much shorter than the counting range. No Geiger counter exhibits an ideally flat plateau characteristic for any considerable range above the threshold voltage. An increase in counting rate with overvoltage is always observed which may be as high as 0.1 per cent per volt in counters that are still considered satisfactory for many applications.

A portion of the slope can be attributed to a real increase in sensitivity, but the remainder arises from increasing numbers of spurious counts at high overvoltages. The former effect is largely explained as an increase in volume of the counter through the growth of the electrostatic field at its ends. Of course, any misalignment of the electrodes, such as the wire being cocked at an angle to the axis of the cylinder, will increase the sensitivity with increasing overvoltage by causing different portions of the counter to exhibit different threshold voltages. Finally, any inefficiency from failure to mature a complete discharge would be lessened by an increase in overvoltage, since the number of photons per discharge increases with overvoltage and improves the probability of spreading the discharge completely. The electrostatic effects can be minimized, in general, by carefully aligning the electrodes, making the length-to-diameter ratio as large as convenient, polishing the anode to remove sharp points, and shielding the ends of the wire with insulating sleeves so as to limit the expansion of the sensitive volume beyond the ends of the cylinder. In the preparation of most counters these precautions are more or less routine, so that spurious pulses generated by the discharge itself are usually the major contributors to plateau slope.

The most serious source of plateau slope in Geiger counters is a type of spurious counts that appear in the form of "afterdischarges" or trains of counts following a valid count. In some counters these multiples appear almost immediately above threshold; in all counters they appear at sufficiently high overvoltages. The voltage region in which these trains of multiple counts begin to appear in appreciable numbers marks the limit of the useful plateau range. Certain fillings, such as argon and alcohol, which show no spurious pulses at overvoltages of 100 to 200 volts, produce very flat plateaus. If the argon is of spectroscopic purity (99.9 per cent) and the alcohol is free of air and water, a plateau slope less

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[24] P. B. Weisz, "Starting potential of the Geiger-Mueller counter discharge," *Phys. Rev.*, vol. 74, pp. 1807–1812; December, 1948.

[25] J. A. Simpson, "The theory and properties of low-voltage radiation counters," MDDC report 870, Declassified, 1947.

[26] S. H. Liebson and H. Friedman, "Self-quenching halogen-filled counters," *Rev. Sci. Instr.*, vol. 19, pp. 303–307; May, 1948.

[27] R. D. Present, "On self-quenching halogen counters," *Phys. Rev.*, vol. 72, pp. 243–244; August, 1947.

than 0.01 per cent per volt may be obtained. A commercial grade of argon (98 per cent), on the other hand, produced slopes from 0.05 to 0.15 per cent per volt, and contamination with air increased the slopes proportionately.[28] An optimum concentration of quenching admixture was also observed which was about 5 per cent for alcohol. Larger concentrations increased the slope. This behavior could be explained by failure of an increased number of discharges to develop fully because of the suppression of photon emission in the avalanches. A mixture of 20 per cent of alcohol in argon increased the slope to 0.05 per cent per volt. The behavior of alcohol-argon is also typical of helium and neon and many of the more commonly used hydrocarbon quenching admixtures, such as ether, ethyl acetate, amyl acetate, and ethylene. In contrast, many spurious counts were observed[17] when alcohol was used with O_2, N_2, or H_2. For a mixture of hydrogen and alcohol, 27 per cent of the counts observed in the middle of the plateau were spurious; in oxygen and alcohol the fraction of spurious counts was 10 per cent.

Although a counter may initially exhibit a very flat plateau, the slope invariably increases with use. The rate at which this proceeds initially and over longer periods of use varies with the particular gas mixture. In argon, with alcohol admixture, the slope may increase considerably at first, then remain relatively unchanged for a major portion of the useful life, and finally deteriorate very rapidly. Some mixtures show a tendency to recover when not in use. All of these effects reflect the contamination of the gas mixture by decomposition products of the discharge and the correlated loss of the optimum concentration of quenching constituent.

The process responsible for the major portion of the spurious pulses observed in counter tubes is positive-ion bombardment of the cathode. As the overvoltage is raised, the number of positive ions per discharge increases. Since the emission of secondary electrons is directly proportional to the number of ions arriving at the cathode, the number of spurious counts should increase with overvoltage. Because of the well-defined time require for the positive-ion sheath to traverse the interelectrode space, spurious pulses arising from secondary emission are readily recognized. On an oscilloscope screen, trains of spurious pulses at high overvoltage have the appearance of relaxation oscillations. The successive pulses in a train are uniformly spaced in accordance with the nature and pressure of the vehicular gas and the overvoltage, as predicted by the dependence of ion mobility on pressure and field strength. Figs. 10, 11, and 12 illustrate the increasing length of the trains of multiple pulses with increasing overvoltage or decreasing concentration of quenching admixture; the increase in spacing of multiples as the mobility of the positive ions is reduced by increased pressure; and the dependence of the mobility, as reflected by the spacing of pulses, on the collision cross sections of the rare-gas atoms. Before arriving at the condition of continuous corona discharge, the number of pulses in individual trains may reach thousands without destroying the perfect spacing between pulses.

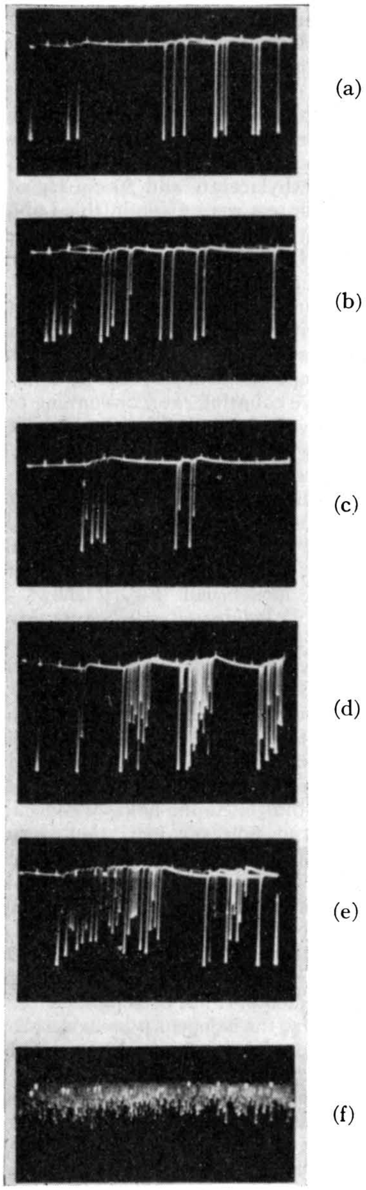

Fig. 10—Appearance of multiple pulses with insufficient admixture of quenching vapor. All traces were photographed at an overvoltage of 100 volts. Initial filling was argon, 20 cm Hg, plus CH_2Br_2, 0.5 mm Hg, which showed single pulses (trace A). Successive dilutions of the CH_2Br_2 were made by pumping the mixture to 10 cm Hg and restoring 10 cm of pure argon. Traces B to F illustrate the appearance of increasing numbers of spurious counts with removal of the quenching agent.

The idea behind most procedures for treating counter tubes prior to filling is to produce a high work function at the cathode surface, and thereby reduce spurious pulses due to secondary emission. In many instances the effect of adsorbed polyatomic molecules on the metal surface is to increase its work function more markedly than most of the treatments to oxidize, or make the surface passive, which have so often been recommended in the literature. Measurements of the photosensitivity of an alcohol-argon counter with a clean copper cathode show that the photoelectric threshold is depressed toward the ultraviolet as more alcohol is admixed with the argon. During use, the discharge decomposes the alcohol and the threshold climbs steadily back toward the visible. When using low-work-function-electrode materials, such as aluminum or magnesium, the work function must be consider-

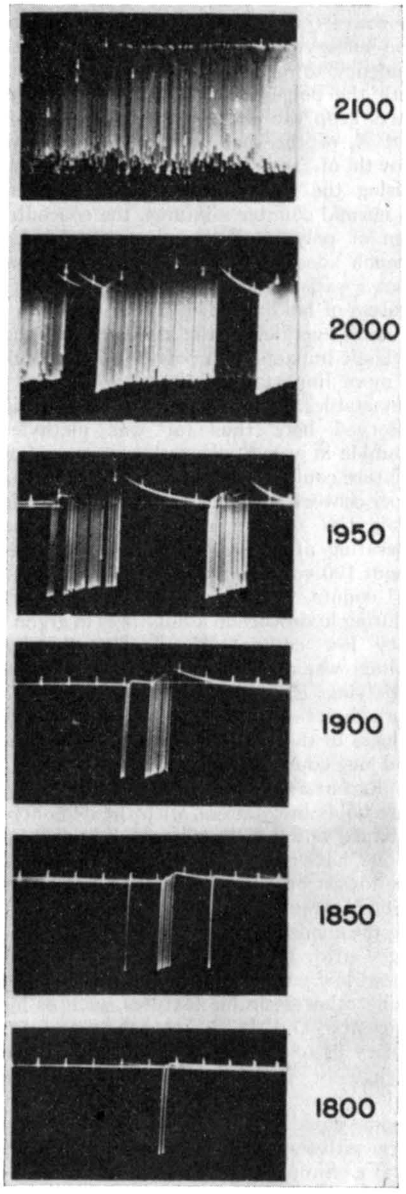

Fig. 11—Development of spurious pulses at high overvoltages. The filling was 20 cm Hg of argon plus 10 mm Hg of CH_2Br_2. Threshold was 1,500 volts. At overvoltages in excess of 300 volts, multiple pulses, appear with uniform spacings characteristic of secondary emission due to positive ion bombardment of cathode. Higher overvoltages increase the average length of the trains of pulses and their frequency of occurrence. Marker pulses are 2,500 microseconds apart.

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[28] S. A. Korff, W. B. Spartz, and J. A. Simpson, "Summary report on neutron counter work," MDDC Report 1704.

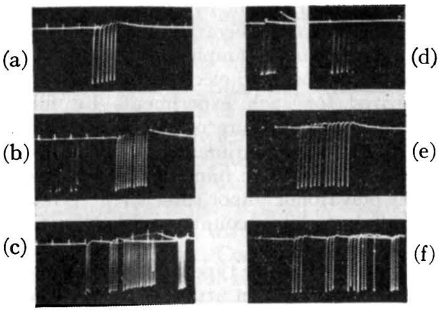

Fig. 12—Effect of gas mixture on spacings between multiple pulses. Traces (a), (b), and (c) were made with 75, 35, and 15 cm Hg of argon respectively and a constant admixture of 10 mm Hg of CH_2Br_2. As the pressure of the argon was reduced, the mobility of the positive ions increased, and the intervals between pulses became shorter. Trace (d) illustrates the greater mobility in helium as compared to argon. All markers are spaced 2,500 microseconds apart, but the right-hand portion of trace (d) is expanded. Traces (e) and (f) show the opposite trend toward decreasing mobility in a heavier gas such as Xe.

ably increased by chemical treatment or by deposition of a very thin layer of a more suitable surface, such as copper, before satisfactory counting can be obtained. Glow discharging in an active gas, before filling is often effective in subsequently preventing spurious counts. Several more extreme treatments have been described, such as mechanically coating the cathode with a very thin layer of a high-work-function surface; for example, a coating of lacquer. The influence of such a coating can be judged from its effect on the photoelectric threshold. Because the lower-energy photoelectrons released at threshold cannot penetrate the thin coating, the photoelectric limit appears to be shifted toward the ultraviolet.

A less-important class of spurious counts are those attributable to the charging of particles or thin layers of insulating material on the cathode. During the discharge, positive ions may remain bound to these insulating surfaces, or the particles may acquire charge as a result of photoelectric emission. Subsequently, spurious counts may be triggered by electrons released in the neighborhood of these charged spots. Experiments with plane-parallel electrodes[29] demonstrated the presence of an electron current decreasing roughly exponentially with time, following the termination of a glow discharge. A measurable current was observed for fully 15 minutes with nickel electrodes coated with collodial graphite and magnesium oxide. After prolonged baking to remove the oxide, this after-discharge current almost entirely disappeared. The effect of irradiation was demonstrated by an experiment[30] in which parts of a counter tube were exposed to intense X rays and the counter subsequently reassembled. A much higher background was then observed, which decayed slowly with time. Many counters go over into an unbroken chain of counts when the overvoltage exceeds the limit of the plateau and do not recover when returned to what was previously normal operating voltage. The applied voltage must then be dropped below threshold for at least a few seconds before such tubes recover. This general behavior closely resembles the phenomena observed in the aforementioned experiments with MgO coatings and irradiated electrodes.

LIFE OF SELF-QUENCHING COUNTERS

Most self-quenching counters exhibit similar symptoms of aging. The threshold voltage rises, the plateau slope increases, and multiple pulses appear at progressively lower voltages. Many tubes become increasingly photosensitive. Some counters may be brought into self-sustained discharge above the plateau, yet recover immediately when returned to operating voltage; whereas others are permanently destroyed if brought into continuous discharge, even momentarily. Most of these observations are understandable in terms of the decomposition of the quenching admixture in the course of the discharge. A typical counter initially contains approximately 10^{20} polyatomic molecules. About 10^{10} of these molecules are ionized in each discharge, and dissociate when they reach the cathode wall. It seems necessary, therefore, to accept an upper limit of about 10^{10} counts for the maximum life of a self-quenching Geiger counter containing polyatomic molecules. A simple demonstration of the breakdown of the polyatomic constituent is obtained by attaching a sensitive manometer to a counter tube under life test. The increase in total pressure contributed by the partial pressures of the end products of the discharge is readily observed. It is now believed that the aging may generally be attributed to a combination of two processes: (1) an alteration in the optimum gas composition resulting from decomposition of the quenching vapor, and (2) the deposition on the electrodes of polymerization products manufactured as a result of the discharge. The former process is sufficient to account for most of the deterioration of ethyl alcohol and ethyl acetate fillings. The latter process has been identified with the short-lived performance of methane fillings.

The primary decomposition products[31] are neutral radicals and fragment ions. Mass-spectrometer research in recent years has revealed an abundance of fragment ions formed in electron bombardment of complex molecules, compared to the number of ions of the parent molecules. In some molecules, such as tetramethyllead,[18] the parent ion is not observed at all. Some of the dissociated fragments may combine to form other organic molecules, which may or may not be quenching molecules. It may be reasoned that, starting with a large molecule, a relatively greater portion of the products of the discharge may again have quenching properties. This seems to be generally true. The lifetime of a counter using amyl acetate, for example, is about ten times as long as that obtained with ethyl-alcohol admixture. Eventually, all the larger molecules must be broken down into the lighter fractions, including nonself-quenching gases such as hydrogen and oxygen.

In the case of methane, tubes are found to fail at between 10^7 and 10^8 counts, which is insufficient to account for decomposition of enough of the original admixture to spoil the tube. It has been shown[32] that the decomposition of methane yields hydrogen along with saturated and unsaturated hydrocarbons, and a deposit on the cathode cylinder which can be identified as a polymerization product formed from the unsaturated hydrocarbons. This polymerization process is known to occur quite readily in an electrical discharge at the surface of a metal electrode. The failure of counters using propane and butane also appears to be tracable largely to the deposition of dielectric polymers on the cathode surface. Such tubes cannot be restored to operation by refilling with a fresh gas mixture, unless the electrodes are washed with a solvent capable of removing the deposits.

SHORT TIME DELAYS IN THE FIRING OF GEIGER COUNTERS

Coincidence counting is one of the most powerful tools available for the analysis of nuclear-disintegration schemes and cosmic-ray phenomena. In all cases, it is advantageous to reduce the coincidence resolving time to as short an interval as possible, if merely to reduce the number of accidental coincidences which statistically occur in direct proportion to the resolving time. In determining the decay scheme of a nucleus which undergoes a series of radioactive transitions in rapid succession, observations of delayed coincidences can reveal the time relationships in the chain of nuclear radiations. If two transitions follow each other in less than 10^{-8} second, it is experimentally impossible to distinguish the spacing between them with Geiger counters. If, however, the second transition in a sequence follows the first after an average time interval greater than 10^{-8} second, it becomes possible to detect the deviation from simultaneity by delaying the count produced by the first transition long enough to bring it into coincidence with the second. To apply this type of measurement to timing events separated by as little as tenths of a microsecond requires experimental resolution times of a few hundredths of a microsecond. In attempting to decrease the resolving time much below a microsecond, however, many experimenters found inherent uncertainties in the firing times of counters of the order of a tenth of a microsecond,[33] which were entirely distinct from the occasional longer delays of 10 to 100 microseconds resulting from electron attachment to form negative ions.

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[29] A. Guntherschulze, "Electron velocity in insulators at high field strengths and its relation to the theory of electric penetration," *Zeit. Phys.*, vol. 86, pp. 778–786; December 7, 1942.

[30] Mr. Roggen and Mr. Scherrer, "An After-effect of X-ray irradiation on counter tube performance," *Hevl. Phys. Acta*, vol. 15, pp. 497–499; 1942.

[31] S. S. Friedland, "On the life of self-quenching counters," *Phys. Rev.*, vol. 74, pp. 898–901; October 15, 1948.

[32] E. C. Farmer and S. C. Brown, "A study of the deterioration of methane-filled Geiger-Mueller counters," *Phys. Rev.*, vol. 74, pp. 902–905; October 15, 1948.

[33] C. W. Sherwin, "Short time delays in Geiger counters," *Rev. Sci. Instr.*, vol. 19, pp. 111–116; February, 1948.

The maximum resolution achieved with any coincidence arrangement using a pair of Geiger counters depends on the rate of growth of the pulse in each counter following the passage of the ionizing photon or particle. Experimentally, it is observed that, even when a pair of counters of average dimensions are fired by the same high-speed particle, there occurs a relative randomness in firing times with an average difference of as much as 0.2 microsecond. Short time delays in firing of a counter may be attributed to two sources: (1) the electron-transit time in the avalanche; (2) the time required to develop the initial part of the ion sheath after the first electron avalanche reaches the wire. The former delay arising from electron-transit time is essentially independent of overvoltage, whereas the latter delay, involving growth of the ion sheath, decreases with increasing overvoltage. As was mentioned earlier, the elementary process of avalanche production, beginning at a distance of a few wire diameters from the anode, requires about 10^{-9} second. The collection time for the triggering electron and single Townsend avalanche which it creates, will obviously depend on the radial distance at which the primary electron is produced. To compute this time it is necessary to know the velocity of the electron at all distances from the wire. However, since an electron starting at the cathode must traverse the first half of the radial distance to the wire at nearly thermal velocities, its motion in the outer $r/2$ portion of its path counts for almost all of the collection time. The average energy acquired per mean free path over the first half radius from the cathode is about 1/4 ev., which corresponds to an average velocity of about 3×10^7 cm/sec. The maximum possible transit time in a tube of one centimeter radius will therefore be somewhat greater than 3×10^{-8} second.[34] For an electron starting at intermediate radial distances, the transit time is roughly proportional to the square of the distance. In counters of larger diameters, transit times can, therefore, reach values in excess of a microsecond. Measurements[35] on a tube 7 cm in diameter revealed transit time delays of 0.3 to 2 microseconds.

The portion of the delay attributable to the rate of growth of the ion sheath depends on the sensitivity of the detector amplifier, the position along the length of the tube at which the sheath starts to develop, and the overvoltage. During the first tenth of a microsecond required for the sheath to spread a distance of a few millimeters, the rate of rise of the pulse on the wire may be less than one volt per tenth of a microsecond. Obviously, a wide-band, high-sensitivity amplifier would be required to detect the pulse within this time interval. The rate of rise increases rapidly after the first 10^{-7} second, depending somewhat on whether the counter is triggered at the center or near one end. At the center, the discharge may spread in both directions; whereas, at either end of the tube, the discharge can propagate only in the direction of the opposite end. The slope of the pulse during the spread of the discharge is roughly twice as steep in the former case. The behavior with change in overvoltage is also readily understandable, since the discharge is matured by photon emission and absorption, and the abundance of photons per avalanche increases with higher overvoltage.

It is clearly indicated, then, what steps may be taken to achieve the fastest possible coincidence resolving times. The smallest diameters and lowest filling pressures consistent with other experimental requirements should be selected to minimize transit time fluctuations. A sensitive wide-band amplifier and operation at high overvoltage will make it possible to detect the pulse in the earliest stage of its growth. Resolving times as low as 0.035 microsecond without coincidence losses due to random time delays were obtained in experiments by Mandeville and Scherb,[36] with argon-ethyl ether fillings and a fast coincidence circuit.

COSMIC-RAY EFFICIENCY

In the majority of Geiger-counter-tube types, it may be safely assumed that a single ion pair formed anywhere within the volume of the Geiger counter will trigger a discharge. In detecting the passage of an ionizing particle, such as a cosmic-ray meson, the efficiency can ordinarily be made greater than 99.5 per cent by selecting a heavy gas and filling to a relatively high pressure. The rare gases, except for helium, yield many ions per centimeter of path when traversed by a high-speed cosmic-ray particle. The values of the specific ionization (ions per cm per atmosphere) in neon, argon, and xenon are 12, 29, and 44, respectively, but the values for helium and hydrogen are no greater than about 6. Since the number of ions produced per centimeter of path fluctuates statistically, there is always a chance that the particle may traverse the counter without producing an ion pair. The average number of electrons N left behind by a meson if it traverses a path length d in the counter is npd, where n is the specific ionization, and p is the fraction of atmospheric pressure. The probability of not producing an electron is, therefore, e^{-N} and the efficiency ϵ is given by

$$\epsilon = 1 - e^{-N}. \qquad (4)$$

For example, when the gas in the counter is argon at 1/10 atmospheric pressure, and the track length through the tube is 2 cm, 6 ions per meson are produced, on the average, and the efficiency is 99.8 per cent. If, now, the particle penetrates the counter close to the wall, traversing about 1/6 centimeter, N becomes equal to 1, and the efficiency is only 63 per cent. In the same way, one finds that the efficiency for small counters and for counters filled with hydrogen or helium is considerably lower. For 90 per cent efficiency in a 2-cm path, it is necessary to use about 15 cm Hg pressure of hydrogen or helium, as compared to 3 of argon.

In certain cosmic-ray experiments, low efficiencies are deliberately sought so as to distinguish, for example, between heavily ionizing mesons and electrons. Counters are prepared for such experiments by filling with a lower pressure of hydrogen or with three or four centimeters of helium, to which is added the minimum amount of a light polyatomic vapor sufficient to produce a self-quenching counter with a usable plateau.

There is another type of inefficiency associated with electron attachment which was first demonstrated[37] in studies of coincidence counting, with cosmic-ray telescope arrangements. In the region near the cathode, the combined effects of low field strength and production of relatively few ion pairs makes electron capture to form negative ions sufficiently probable to have a marked effect on efficiency. The heavy negative ions drift slowly into the high-field region, where the negative charge may detach and initiate a delayed discharge, or the ion may retain its charge and not produce an avalanche at all. By varying the resolving time[38] of the coincidence circuit used with an oxygen-filled counter from 0.2 to 70 microseconds, the efficiency of coincidence counting was altered from 50 to 80 per cent. When the oxygen was diluted to 6 per cent of an oxygen-argon mixture, the efficiency remained about 96 per cent from 0.2 to 600 microseconds. The portion of the inefficiency which disappeared with increasing resolving time represented delayed counts originating from negative ions which gave up their electrons near the wire from 10 to 100 microseconds after their attachment. The inefficiency which is unaffected by resolving time represents the fraction of primary ionizing events which do not mature into counts. Although this inefficiency is only barely detectable in argon plus 6 per cent oxygen, it is very pronounced in tubes containing admixtures of the halogens, halogenated hydro-

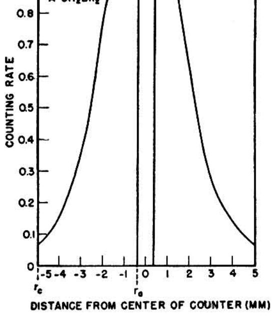

Fig. 13—Variation of counting rate with radial distance from the anode. The counter tube was scanned with a fine pencil of X-rays traveling parallel to the anode. (After Friedman and Birks, in footnote reference 39.)

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[34] S. A. Korff, "On the rise of the wire potential in counters," *Phys. Rev.*, vol. 72, pp. 477–481; September, 1947.

[35] H. Den Hartog, F. A. Muller, and N. F. Verster, "Time lags in Geiger-Muller counters," *Physica*, vol. 13, pp. 251–264; May, 1947.

[36] C. E. Mandeville and M. V. Scherb, "Disintegration schemes and the coincidence method," *Nucleonics*, vol. 3, pp. 2–12; October, 1948.

[37] J. C. Street and R. H. Woodward, "Counter calibration and cosmic ray intensity," *Phys. Rev.*, vol. 46, pp. 1029–1034; December, 1934.

[38] M. E. Rose and W. E. Ramsey, "On time lags in coincident discharges of Geiger-Muller counters," *Phys. Rev.*, vol. 59, pp. 616–617; April, 1941.

carbons, ammonia, or sulphur dioxide. Fig. 13 shows the response to a collimated beam of X-rays passing axially down an end-window counter tube at various radial distances from the cathode.[39] With a filling of argon plus methylene-bromide admixture, the efficiency decreased from close to 100 per cent near the wire, to only a few per cent at the cathode. Exposed to cosmic rays this tube showed an over-all efficiency of about 15 per cent. Corresponding measurements are shown for chlorine and argon.

SOFT X-RAY COUNTERS

A counter tube for detection of soft X-rays can be designed so as to produce a count for virtually every quantum which enters the tube. In early work with X-ray counters, relatively low pressures of filling gases were used, and ionization of the gas played a minor role in triggering the counters. The X-ray beam was usually directed at the cathode cylinder, and released photoelectrons which initiated the counts. The X-ray photoelectric yield of any element reaches a maximum on the short-wavelength side of its X-ray critical-absorption limit. For wavelengths longer than those associated with the critical absorption, the absorber is relatively transparent, yielding few photoelectrons. By selecting for the cathode a material whose *K* absorption limit fell at a slightly longer wavelength than the radiation being measured, it was possible to detect about 15 per cent of the quanta which struck the cathode,[40] as in the the case of a zirconium cathode used to measure X rays generated at 30 kev ($\lambda_{\max}=0.6$ Å).

The form of counter tube best suited to the measurement of soft X-ray beams is the end-window type, filled with a gas capable of absorbing a large fraction of the radiation admitted in the direction of the axis of the tube. The absorption of X rays of wavelengths softer than 0.5 Å is almost entirely a photoelectric process in heavy gases such as argon, krypton, and xenon. It is, therefore, permissible to assume that the percentage of an X-ray beam absorbed in the counter-tube gas represents the quantum counting efficiency, provided that each ejected photoelectron triggers a discharge. If argon is the vehicular gas, it strongly absorbs the *K*-series radiations of elements up to about Zn (30). Krypton (36) whose critical X-ray absorption falls at 0.9 Å, is an efficient absorber of wavelengths shorter than this limit, and also matches the absorption in argon at the longer wavelengths. Xenon (54) absorbs strongly throughout this entire region of the spectrum. Fig. 14 illustrates the absorption characteristics of these three gases in the wavelength range from 0.4 to 2.4 Å.[39] It is apparent that efficiencies approaching 100 per cent are attainable over a large portion of this spectral range, if the proper gas is used at sufficiently high pressure or if a long-enough gas path is provided to absorb the X-ray beam.

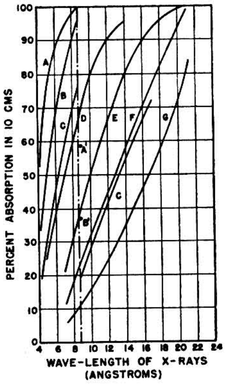

Fig. 14—Absorption of soft X rays in 10 centimeters of the rare gases at various pressures. A—krypton, 76 cm Hg; B—krypton, 40 cm Hg; C—krypton, 20 cm Hg; D—xenon 20 cm Hg; E—argon, 76 cm Hg; F—argon, 40 cm Hg; G—argon, 20 cm Hg; A′—continuation of A; B′—continuation of B. (See footnote reference 39.)

The most transparent, yet vacuum-tight, windows for X-ray counters are in-blown glass bubbles, mica, beryllium, and Lindemann glass (consisting mainly of lithium tetraborate). Glass-bubble windows of thicknesses between 0.5 mg/cm² and 1.0 mg/cm², with apertures 2 centimeters in diameter, are strong enough to support atmospheric pressure on the concave side and still transmit, 1,000 ev X rays. Table II indicates the X-ray transparencies of mica, beryllium, and Lindemann glass at a few wavelengths in the soft X-ray region.

TABLE II

Window	Transmission (per cent) CrK_α (2.27 Å)	 FeK_α (1.94 Å)	 CuK_α (1.54 Å)
0.020 inch Lindemann	4.5	14	38
0.010 inch Lindemann	22	37	61
0.001 inch Aluminum	37	53	71
0.001 inch Mica	40	56	74
0.0005 inch Mica	64	75	86
0.020 inch Beryllium	65	76	86

At MoK_α (0.74Å) ,all the windows listed above transmit in excess of 90 per cent of the X rays.

Typical tube constructions are illustrated in Fig. 15. With glass or mica windows, the active counting region can be brought up close to the window. Beryllium, and aluminum windows are highly transparent, but introduce the difficulty of insulating the window from the cathode, or retracting the anode to eliminate discharging to the window. The resultant dead space immediately behind the window somewhat reduces the efficiency of the counter.

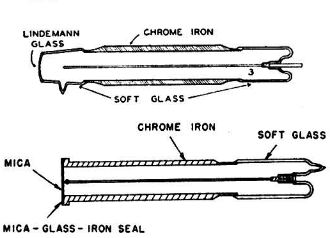

Fig. 15—End-window constructions for soft X-ray counters.

A beryllium window is particularly useful when it is necessary to measure soft X rays in the presence of beta rays. For example, 5-year Fe^{55} decays by *K*-electron capture into Mn^{55}, which then emits 5.9 kev X rays. Fe^{59} has a 47-day half life, and emits beta rays with a maximum energy of 0.46 Mev and hard gamma rays. An argon counter with a beryllium window, 0.4 mm thick, detects about 50 per cent of the soft X rays of Fe^{55} but less than 2 per cent of the Fe^{59} betas. The ratio of sensitivities can then be inverted by using a thin mica window and helium, which will respond to every beta particle entering the tube, but cannot absorb the X rays.

GAMMA-RAY COUNTERS

As the frequency of the electromagnetic radiation increases beyond the soft X-ray region, the photoelectric absorption in the gas assumes an insignificant role. Most gases used in counter tubes do not appreciably absorb photons whose energies exceed 60,000 or 70,000 electron volts, and direct ionization of the gas is negligibly small. Hard X rays or gamma rays are detected by virtue of the ionization of the counter gas by secondary photoelectrons, Compton recoil electrons, and electron-positron pairs produced within the cathode material. For the lighter elements and higher frequencies of gamma rays, the absorption is almost entirely the result of Compton scattering. At the other extreme of higher atomic numbers and softer radiation, photoelectric absorption becomes most important. Electron-positron pairs do not appear below 1.02 Mev, the sum of the mass energies of the two particles. The cross section for pair production increases slowly with the excess of energy above this threshold, and is proportional to atomic number. The photoelectric absorption coefficient is approximately proportional to the cube of the atomic number, and decreases rapidly with increasing frequency. At 1 Mev, the photoelectric absorption coefficient in copper is already reduced to roughly 2 per cent of the Compton scattering coefficient. In the very heavy elements, however, the photoelectric effect remains relatively important up to much higher energies. At 2.6 Mev, the photoeffect in lead is still about 15 per cent of the Compton scattering. Pair production becomes comparable to Compton effect at much higher energies. In lead, gamma rays of 5 Mev produce about one positron for every three Compton recoil electrons. The same ratio is reached in copper at closer to 10 Mev, and in aluminum at about 15 Mev. The combined effect of all three processes contributing secondary electrons is to make the counting efficiency roughly proportional to gamma-ray energy, if the counter is constructed of a light element such as copper. Cathodes of heavier elements—lead, bismuth, or gold—raise the efficiencies to a pronounced degree at both the low and high energy extremes.

In many nuclear experiments, such as the determination of reaction yields, it is necessary to know the absolute counting

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[39] H. Friedman and L. S. Birks, "Geiger counter spectrometer for *X*-ray fluorescence analysis," *Rev. Sci. Instr.*, vol. 19, pp. 323–331; May, 1948.

[40] H. M. Sullivan "Quantum efficiency of Geiger-Müller counters for X-ray intensity measurements," *Rev. Sci. Instr.*, vol. 11, pp. 356–362; November, 1940.

efficiency at particular wavelengths. In order to compute what percentage of gamma-ray quanta of a given energy incident on a Geiger counter will trigger counts, it is essential to understand how the number of secondaries injected into the gas of the counter depends upon the thickness and material of the cathode. If, for example, the thickness of the cathode wall is much less than the range of the secondaries, almost all the secondaries will enter the gas and produce counts; but, by the same token, the fraction of the primary beam converted to secondaries will be small. On the other hand, when the thickness is much greater than the range of the secondaries, the absorption of primary radiation may be relatively great, but the secondaries produced at depths from the inner wall surface greater than the maximum recoil-electron range cannot emerge to contribute counts. This behavior is illustrated in Fig. 16, computed for 2-Mev gamma rays entering aluminum. An optimum thickness exists which produces the maximum number of secondaries per primary quantum. This thickness is of the order of the maximum range of the secondaries in the cathode material.

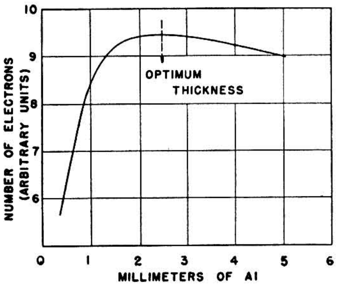

Fig. 16—Ratio of secondary electrons to primary gamma rays (2 Mev) emerging from aluminum absorbers of different thicknesses.

The Compton electrons exhibit a roughly exponential absorption as a consequence of multiple scattering and the dependence of recoil energy on angle. Let an absorption coefficient μ_2 be assigned to the recoil electrons, and let μ_1 represent the linear absorption coefficient for gamma rays. It then can be shown that, for cathode thicknesses equal to or greater than the optimum, the ratio R of the number of secondaries emerging from the cathode to the number of primary quanta transmitted is, approximately,

$$R = \frac{\mu_1}{\mu_2 + \mu_1}. \qquad (5)$$

This ratio is very nearly the efficiency of the counter. For example, a 2-Mev gamma ray, whose absorption coefficient in Al is about 0.12, produces Compton recoil electrons having an absorption coefficient of about 20. The efficiency according to (5), should be about 0.6 per cent. At 1.0 Mev, μ_1 is 0.17, and μ_2 about 55, which should reduce the efficiency to about 0.3 per cent. It is approximately true for lighter elements, such as Al and Cu, that the efficiency in the gamma-ray region from 0.2 to 3 Mev is proportional to the energy, and increases at the rate of about 1 per cent per Mev.

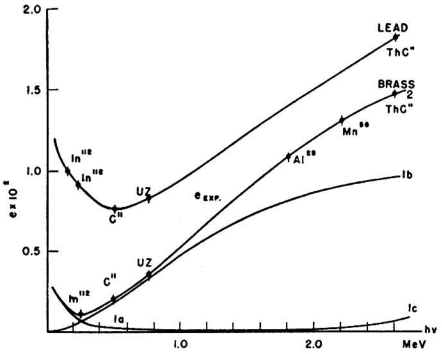

Fig. 17—Efficiencies of gamma-ray counters with brass or lead cathodes in the spectral range from 0.1 to 2.6 Mev. Curves 1(a), 1(b), and 1(c) are the theoretical contributions from photoelectric effect, Compton scattering and pair production in brass. Curve 2 for brass and that for lead are experimental. (See H. Bradt *et al.*, footnote reference 44.)

The wavelength dependence of the contributions to counting efficiency[41] for each of the three absorption processes is shown in Fig. 17 for a copper cathode. The major contribution to the efficiency comes from Compton scattering. When the cathode is made of a heavier element, the efficiency is higher because of the more important contributions from photoelectric absorption and pair production. Fig. 17 also shows the total efficiency curve for lead. Since the Compton effect is independent of atomic number, the difference between the Pb and Cu curves represents the enhanced photoelectric contribution at lower frequencies and pair production at higher frequencies.

Considerable numbers of Geiger-counter survey instruments are being used to monitor radioactive contaminations in atomic-energy activities and X-ray laboratories, and in many cases the meter readings are calibrated in roentgens. It is interesting to apply some of the above data on efficiency to the problem of the ratio of counting rate to roentgen dose at various wavelengths. If, for example, the counting rate per milliroentgen per hour is assumed to be 100 cps at 1 Mev, then a copper-cathode counter will deliver about 135 cps and a lead counter 106 cps at 2 Mev, for the same dose rate. This ratio of counts to roentgens has a minimum somewhere between 0.1 and 05. Mev. On the low-frequency side of the minimum, the counting rate and roentgen dosage rate diverge widely.

Several years ago, Trost[42] attempted to apply counters to roentgen dose measurements under 0.5 Mev in connection with stray radiation from X-ray apparatus. Using a typical metal-in-glass counter tube, he found it possible to keep the ratio of counts to roentgens constant within ±12 per cent between 60 and 120 kv. When a filter combination consisting of 1 mm of tin plus 1 mm of brass was interposed between the source and the tube, the curve of counts versus roentgens was flat to ±10 per cent from 120 to 300 kv. To include the very soft radiation under 60 kv, he constructed a tube with a plexiglass wall, 1 mm thick, and operated it slightly below Geiger threshold in the region of limited proportionality. For energies in excess of 35 kev, the current delivered by this tube paralleled an "air wall" ionization-chamber response within ±10 per cent. These results are illustrated in Fig. 18 reproduced from the literature.[43]

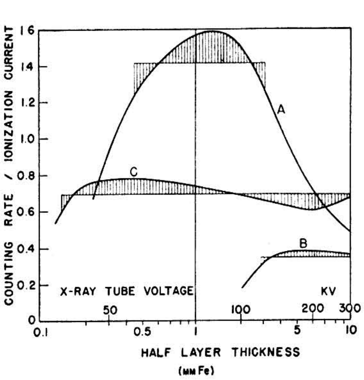

Fig. 18—Ratio of ionization-chamber current to output of a Geiger counter: (A) Unfiltered; (B) filtered; and a proportional counter (C) made of plexiglass. (See Trost, footnote reference 42.)

METHODS OF IMPROVING THE GAMMA-RAY EFFICIENCY

Any construction which increases the area of cathode surface per unit volume of the counter will increase the number of secondary electrons injected into the gas, and thereby increase the efficiency. The exposed inner surface of a cylindrical cathode may be increased by a factor of $\sqrt{2}$ over that of a smooth surface by cutting 45-degree threads on the inside or by a factor of $\pi/2$ by employing a closely wound helix of 16- or 20-gauge wire as the cathode. The greatest advantage was gained by the substitution of a wire-mesh screen for the solid-wall cathode.[43] The optimum mesh was found to be about 100 wires per inch, and gave about a 50 per cent improvement in efficiency over a smooth-walled cathode of similar material. Part of this gain was attributed to the ability of the electric field to penetrate the apertures in the mesh and draw in electrons formed on the outside.

Bundling large numbers of smaller-diameter tubes within the volume of a single large tube is another simple method of increasing efficiency, particularly when dealing with a collimated beam of radiation. Since perhaps 99 per cent of the gamma-ray beam is transmitted through the walls of the first cylinder, the second cylinder in the path of the rays has almost as much chance of producing a count as the first. Ten

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[41] H. Bradt, P. C. Gugelot, O. Huber, H. Medicus, P. Preiswerk, and P. Scherrer, "Sensitivity of counter tubes with lead, brass, and aluminum cathodes for gamma rays in the energy interval 0.1 Mev-3Mev," *Helv. Phys. Acta*, vol. 19, pp. 77–90; Sec. II, 1946.

[42] A. Trost, "Application of counter tubes to nondestructive testing," VDI—*Zeitschrif*, vol. 85, pp. 829–833; October, 1941.

[43] R. D. Evans, and R. A. Mugele, "Increased gamma ray sensitivity of tube counters and the measurement of the thorium content of ordinary materials," *Rev. Sci. Instr.*, vol. 7, pp. 441–449; December, 1936.

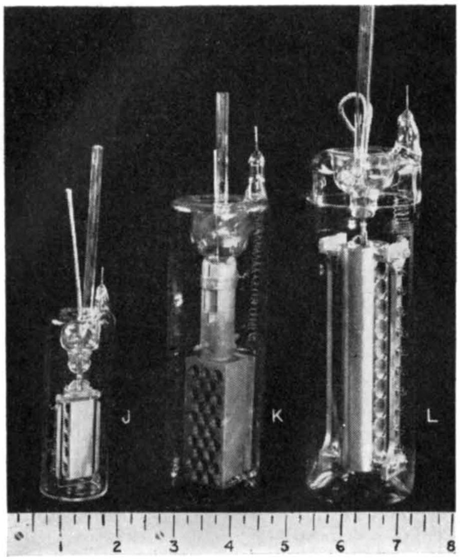

Fig. 19—Multiple counter tubes in parallel combinations.

counter cylinders in line may, therefore, yield about nine times as many counts as a single counter placed in the path of a parallel bundle of rays. The counters shown in Fig. 19 were intended for use in this way. If, however, a number of smaller-diameter cylinders are bundled in place of a single large tube of comparable over-all dimensions, the gain in efficiency for detection of an isotropic flux of radiation is not very great unless a very large number of tubes is used. The relative efficiencies of the bundle of tubes and the equivalent simple tube are given by the ratio of the sum of the diameters of the individual tubes to the diameter of the simple large tube. For a bundle of seven tubes, the ratio is 7/3; for nineteen tubes, the improvement in efficiency is only 19/7.

Perhaps the most successful multi-element tubes designed to increase efficiency were described by Hare in a series of patents[44] filed in 1941–1943. It is not necessary to retain the coaxial-cylinder arrangement in order to obtain a Geiger-counting plateau. Because of the concentration of the field near the wire, the plateau is relatively insensitive to the shape of the cathode. For example, a plane electrode may be substituted for the cathode cylinder (Fig. 20(a)). This configuration may be expanded in one dimension, as shown in Fig. 20(b), and finally in two dimensions to form a multiplicity of both plates and wires, as in Fig. 20(c). The efficiency of such an assembly is approximately equal to the number of plates, even when as many as ten plates are used, and does not depend very much on orientation. Theoretically, the limit to the efficiency obtainable with such structures may approach 30 to 40 per cent. Practical restrictions on the number of plates employed would be governed by the mechanical limitations on the closest spacings. Hare stated that spacings between plates of 2 millimeters were successfully employed.

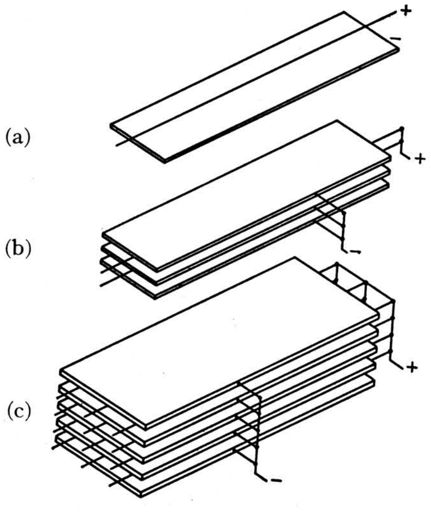

Fig. 20—Multiple plate and wire construction of a gamma-ray counter.

The extent to which the geometry of the counter may deviate from the simple coaxial cylinders, and still retain full volume sensitivity, depends on the nature of the gas in the counter. With the more commonly used "100 per cent efficient" mixtures, such as argon-alcohol, a considerable assymetry is tolerable. However, with halogen admixtures, halogenated hydrocarbons, and other electronegative gases, the loss of sensitivity in the weak-field regions near the corners of a box counter of rectangular cross section, for example, would leave most of that part of the counter volume insensitive to radiation. Recently, Curran and Reid[45] investigated the behavior of box-shaped cathodes with various numbers of parallel-wire anodes, and determined the effects of assymetries in anode positions relative to cathode walls and of anode spacings relative to each other.

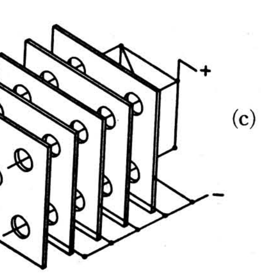

Fig. 21—Perforated disk-type of contruction for a high-sensitivity gamma-ray counter.

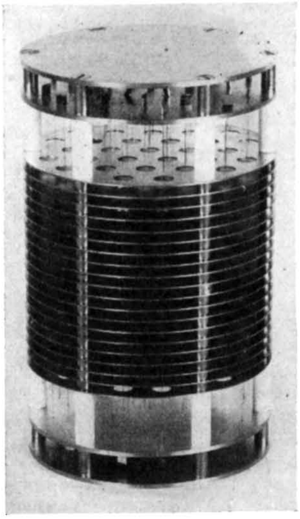

Fig. 22—Photograph of a multiple-disk counter.

Many other arrangements to increase the cathode surface have been suggested. The construction shown in Fig. 21(a) consisting of a wire anode passed perpendicularly through a hole in a plate, will function as a Geiger counter. The sensitive volume of such a configuration extends out considerably farther than the radius of the hole in the neighborhood of the plate. Extending this arrangement, as shown in Figs. 21(b) and (c) and Fig. (22), leads to a structure of stacked disks perforated with holes that are aligned on common cylinder axes. The anode wires are strung axially through the holes. The entire assembly may be compared to a bundle of counters, the effective diameter of each counter being appreciably greater than the hole diameter because of the penetration of the fringing field between the plates. Again, Hare cited the following figures: If the cathode plate was 1 inch in diameter, the hole 5/16 inch, and the plate spacing 0.1 inch, the same number of counts was obtained as with a conventional counter of $1\frac{3}{8}$ inches diameter.

DuMond[46] described a form of multicellular counter in which the cathode structure was a stack of die-cast lead-alloy disks, each disk having a round hole at the center. As shown in Fig. 23, four anode wires are spread out in the form of a spider between each pair of plates, from a common supporting rod extending through the holes in the centers of the disks. This type of tube was used to receive the converging beam of gamma rays from a bent crystal spectrometer designed to measure wavelengths up to 1 Mev. At 0.5 Mev, the counter detected about 8 per cent of the incident quanta.

Another multisection counter, recently described by Beyster and Wiedenbeck,[47] was based upon a simple unit cell, any number of which could be stacked up to produce the

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[44] U. S. Patent Numbers 2,397,073 and 2,397,071 to D. G. C. Hare, 1946.

[45] S. C. Curran and J. M. Reid, "Properties of some new types of counters," *Rev. Sci. Instr.*, vol. 19, pp. 67–76; February, 1948.

[46] J. W. M. DuMond, "High resolving power, curved-crystal focusing spectrometer for short wavelength X-rays and gamma rays," *Rev. Sci. Instr.*, vol. 18, pp. 626–639; September, 1947.

[47] J. B. Beyster and M. L. Wiedenbeck, "Cell-type gamma counter," *Rev. Sci. Instr.*, vol. 19, p. 819; November, 1948.

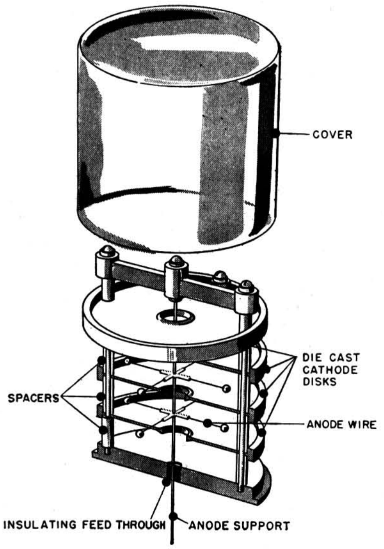

Fig. 23—Multicell gamma-ray counter. (See Du Mond, footnote reference 46.)

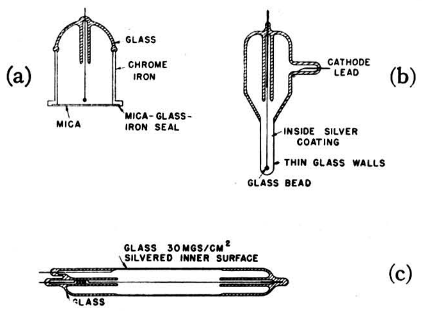

Fig. 24—(a) End-window beta-ray counter.
(b) Thin-walled dipping counter.
(c) Thin-walled beta counter.

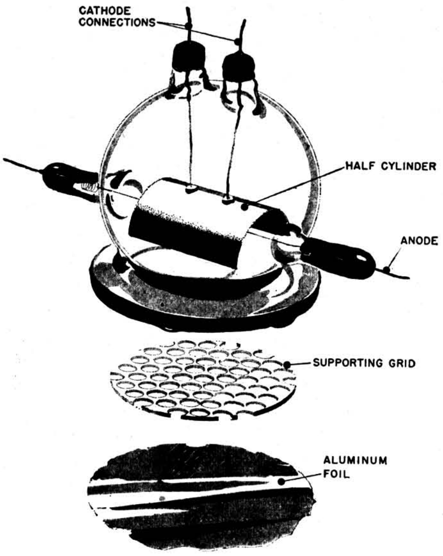

Fig. 25—Beta-ray counter with hemicylindrical cathode.

desired increase in efficiency. Each cell resembled a flat cylindrical cheesebox, made of brass, 4 inches in diameter and ½ inch deep. The anode was a circular loop of 10-mil wire 2 inches in diameter, supported midway between the two faces of the box by glass-insulated "feed-throughs," waxed into the cylindrical wall of the box.

Beta-Ray Counters

The specific ionization of beta rays is high enough so that any particle traversing the interelectrode space of a Geiger counter is almost certain to trigger a discharge. The major problem in designing a beta-ray counter is, therefore, one of providing a suitable window for the particles to penetrate from outside. Alternatively, a demountable counter tube may be used, which can be assembled with the sample inside the envelope of the tube, and then filled with the counting gas mixture.

The simplest type of beta-ray counter closely resembles the ordinary gamma-ray counter except that the cathode wall and envelope are thinned down to the extreme permitted by requirements of mechanical strength. Most familiar of this type is the thin glass-wall tube, about 30 mg/cm², coated with a thin conductive layer of silver, copper, or colloidal graphite (Fig. 24(c)). Because of the fragility of the thin blown-glass portion, attempts have been made to achieve equivalent transparency in metal-wall tubes. Two such tubes have been offered commercially, one fabricated of aluminum with a 0.005-inch wall, and the other of chrome iron with a 0.002-inch wall. The wall thickness of 30 mg/cm² is generally considered to be the minimum compatible with requirements of mechanical strength and vacuum tightness, so that tubes of the thin-wall type are unsuited for use with the softer beta-ray emitters.

The thin-walled counter has been used extensively to measure the artificially induced activities in foils which could be wrapped around the counter and measured after activation. Larger tubes of the same form are well suited to filter-paper measurements, where again the paper is wrapped around the counter, exposing a relatively large surface to the cylindrical beta-ray window. Fig. 24(b) illustrates an adaptation[48] of the thin-walled tube for the measurement of beta activity in liquids. The thin-walled, thimble-shaped end may be dipped directly into the liquid. In still another arrangement, the thin-walled portion of the tube is surrounded by a jacket with provision for admitting the active liquid into one end of the jacket, circulating it about the thin-walled portion, and finally passing it out the opposite end.

The most popular type of beta-ray counter is the end-window tube intended for use with small, flat disks of radioactive deposits. Mechanically, such a tube is identical with the X-ray counters of Fig. 15, but the length of the cylinder is reduced to the minimum consistent with maintaining a flat plateau (Fig. 24(a)). The dimensions are chosen with the intention of providing the maximum solid angle of collection and the minimum response to gamma rays and cosmic-ray background. Reducing the length of the tube relative to its diameter creates end effects which increase the slope of the plateau and decrease its length. Most tubes compromise at a ratio of length to diameter between 3/2 and 2.

A more effective approach to the problem of increasing window area relative to cathode area is to construct a shallow counter bounded by two plane-parallel cathode surfaces. One of these faces is the mica window, conductively coated on the inner surface. The anode wire is mounted parallel to the plane of the window. An approach to such a construction was implicit in the early type of beta counter shown in Fig. 25. The usual cathode cylinder was replaced by a half cylinder with its concave side open toward a thin window. In the tube illustrated, the window was an aluminum foil mounted on a supporting grid. The half cylinder was later succeeded by a multiplicity of half cylinders (Fig. 26(a)), and finally by a flat plate,[49] producing the shallow box form of counter (Fig. 26(b), (c)), one large face of which was the thin window. One or more anode wires were strung parallel to the cathode planes depending on the width of the box. Large counters of this type are widely used as air-proportional counters by laboratories of the Atomic Energy Commission, with a thin nylon film coated with colloidal graphite serving both as the window and one of the cathode plates.[50] In principle, such an arrangement is well suited to beta-ray counting when a vacuum-tight window is provided and the counter is filled with a Geiger counting gas.

Another way of accomplishing the same result was suggested by Beyster and Wieden-

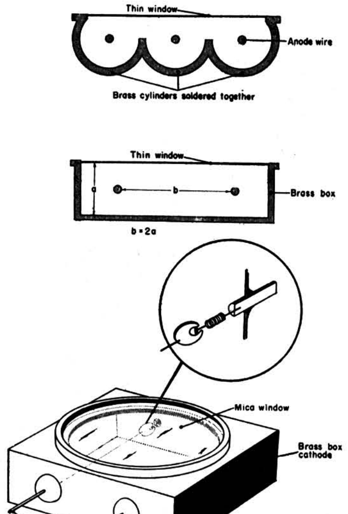

Fig. 26—Development of the flat-box form of beta counter from hemicylindrical cathode structure.

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[48] W. F. Bale, F. L. Haven, and M. L. LeFevre, "Apparatus for the rapid determination of β-ray activity in solutions," *Rev. Sci. Instr.*, vol. 10, p. 193; June, 1939.

[49] R. Thompson and B. Diven, "The multiple wire proportional counter," MDDC Report 99, declassified, July 30, 1946.

[50] J. A. Simpson, Jr., "Air proportional counters," *Rev. Sci. Instr.*, vol. 19, pp. 733–744; November, 1948.

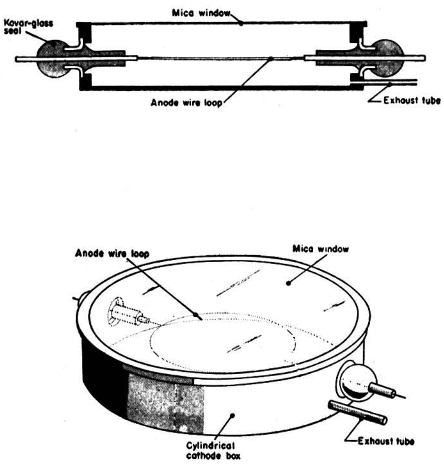

Fig. 27—Low-background beta-ray counter with loop form of anode.

beck[47] in connection with the high-efficiency gamma-ray construction described above. Replacing one face of the shallow cylindrical box with a thin window (Fig. 27) produces a flat-box counter with the same counting geometry as the ordinary end-window counter, but with a minimum of volume and cathode surface.

Mica is the most suitable window for beta-ray counters. It can be split in very thin layers which are strong enough to withstand atmospheric pressure over relatively large areas. The best grade of material for thin windows is imported from Africa. Perhaps the most notable recent advance in the technique of constructing beta-ray counters is the use of powdered glass as the sealing medium for joining mica to soft glass or to chrome iron. In the past, mica windows were attached by methods involving compression seals and lead gaskets, wax joints, or the use of special cements such as selenium. None of these produce satisfactory permanent seals, the tightness of the joints being affected by aging, temperature changes, and reactions between the sealing compounds and the gas of the counter. The powdered-glass technique employs a fine powder of lead-borosilicate glass which has a temperature coefficient of expansion very close to those of soft glass, chrome iron, and mica. The glass is used as a thick water paste, applied with a brush around the rim of the mica and the seating flange of the glass or chrome-iron-tube body. With the mica window in place, the seal is heated to the fusing point of the glass powder, producing a vacuum-tight, inert, and permanent seal.

A common difficulty with mica windows is a tendency to acquire a charge, thereby introducing spurious counts and a hysteresis in the response of the tube to changes in intensity. This effect is minimized in tubes filled with gas mixtures containing electronegative components such as the halogens. Ordinarily, it can be eliminated by making the inner surface of the mica slightly conductive.

One-inch mica windows of 1.5 mg/cm^2 thickness are supplied in commercial tubes. Such windows are adequate for measurements of S^{35} (167 kev) and C^{14} (145 kev), but are not thin enough for tritium, H^3, whose beta rays have a maximum energy under 15 kev. Extremely thin films of materials such as nitrocellulose, formvar, and evaporated silica can transmit electrons with energies as low as 1,000 or 2,000 electron volts. These films are sufficiently vacuum tight and strong enough, when mounted on a fine supporting grid, that semipermanent fillings can be made, which retain satisfactory counting characteristics for a day or longer.

In working with tritium, it is generally desirable to admit the radioactivity directly into the counter as part of the counting gas.[51] The tritium can be converted to HTO water, which may be introduced into the counting mixture as water vapor at a pressure of 1 or 2 mm Hg without seriously damaging the counting characteristics. Alternatively, tritium gas may be electrolyzed from tritium water and used in the same manner as inactive hydrogen as a counter gas. If C^{14} is carried in CO_2, it may be used as the counting gas[52,53] in combination with CS_2 vapor and the aid of an electronic quenching circuit. About 2 cm Hg of CS_2 is used with anywhere from 10 to 50 cm Hg of CO_2, providing thresholds from about 2,000 to 5,000 volts, depending on the tube dimensions.

The screen-wall counter[54] shown in Fig. 28(b) is illustrative of a demountable type in which the source is placed inside the envelope, so as to eliminate the need for a window. Radioactive material to be measured is coated on the inside of the metal sample cylinder. This cylinder can be made of nickel, so that it may be moved within the tube by means of an external magnet. The active volume of the counter is defined by the wire-mesh cathode in the center of the tube. When the sample holder is in alignment with the screen cylinder, as shown in the figure, the counter presents a large solid angle to the source and accommodates a relatively large area of sample. Background count is determined with the sample cylinder drawn to one end of the tube, out of the sensitive region. Any suitable gas mixture may be used. It is recommended that the tube be operated with "drag-in" voltage between the screen and the sample cylinder or outer wall, so as to sweep out positive ions which drift outside the gauze. The disadvantage of this type of counting is, of course, the need for disassembling the tube every time a sample must be changed, a procedure which may consume about 20 minutes between sample measurements.

An apparatus, known as a "gas-flow" counter[55] which provides for quick sample changes and eliminates the inconvenience of disassembling and reassembling the counter tube, and evacuating before refilling, is shown in Fig. 28(a). The sample is brought up close to the mesh cathode through a side tube. Methane, helium, or a mixture of helium and a quenching gas stored in a high pressure tank, is admitted through the input sidearm. The incoming gas flushes the air out of the tube through a bubbling bottle. By maintaining a continuous flow of gas at atmospheric pressure, it is unnecessary to have a perfectly vacuum-tight system. The operating voltages need not exceed 2,500 volts with methane, and are much lower with helium mixtures. The arrangement illustrated in Fig. 28(a) is relatively crude compared to some more recent versions of gas-flow counters which permit the use of larger samples and more efficient geometries.

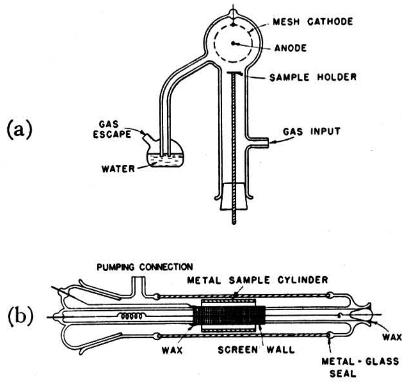

Fig. 28—(a) Demountable windowless beta counters. "Gas flow" beta-ray counter for internal samples.
(b) Demountable beta-ray counter for internal samples.

SIZE LIMITATIONS

There are many problems, particularly in medical physics and in nuclear physics, which call for the use of small-sized probes for gamma- and beta-ray detection. For example, in medical tracer work it may be desirable to determine the location of a radioisotope within the tissue of an animal or human "in vivo." The limitations on the extent to which the dimensions of a Geiger counter may be scaled down have thus far been entirely mechanical. Curtis described[56] what is perhaps the smallest counter yet built. The glass envelope was coated with aquadag on the inner wall to form a cathode cylinder only 0.8 mm inside diameter and a length of 3 mm. The anode was a tungsten wire 0.005 m in diameter. Curtis compared the size of the tube to a number 2 sewing needle, as shown in Fig. 29. The tube was filled with the usual amyl-acetate and argon mixture at 4 cm Hg total pressure, and gave a background count of 20 per hour. Pulse size in such small tubes is comparable to, or greater than, that obtained in larger tubes. Because of the small volume of the tube, it is natural to expect the life to be shorter than in larger tubes, where the number of

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[51] R. Cornog and W. F. Libby, "Production of radioactive hydrogen by neutron bombardment of boron and nitrogen," *Phys. Rev.*, vol. 59, pp. 1046; June 15, 1941.

[52] W. F. Libby, "Measurement of radioactive tracers," *Anal. Chem.*, vol. 19, pp. 2–6; January, 1947.

[53] W. W. Miller, "High efficiency counting of long-lived radioactive carbon as CO_2," *Science*, vol. 105, pp. 123–125; January 31, 1947.

[54] W. F. Libby and D. D. Lee, "Energies of the soft beta radiations of rubidium and other bodies. Method for their determination," *Phys. Rev.*, vol. 55, pp. 245–251; February 1, 1939.

[55] S. C. Brown, "Beta ray energy of H^3," *Phys. Rev.*, vol. 59, pp. 954–956; June 15, 1941.

[56] L. F. Curtis, "Miniature Geiger-Müller counter," *Jour. Res. Nat. Bur. Stand.*, vol. 30, pp. 157–158; February, 1943.

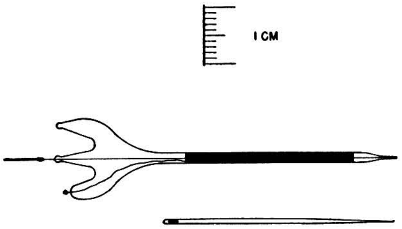

Fig. 29—Miniature Geiger counter. (See Curtiss, footnote reference 55).

molecules dissociated per pulse constitute a smaller percentage of the total number originally present.

At the other extreme, unusually large counters offer no constructional difficulties, but they are inherently slow, have relatively high background rates, and a greater percentage of delayed and spurious counts. To avoid excessively high operating voltages, the anode diameter is ordinarily kept small, while the cathode diameter is increased. The field throughout most of the counter volume is, therefore, relatively weak. As a result, the electron collection time is longer and the positive-ion sheath must cover most of the enlarged distance from wire to cylinder in a weak field, with a consequent increase in the dead time. In the enlarged weak-field part of the counter volume there is also a greater probability for negative ion formation, and delayed counts. Finally, the increased capacitance slows up the recovery of the wire potential and broadens the pulse.

REDUCTION OF DEAD TIME

Stever's experiments[5] demonstrated the existence of a natural dead time of 10^{-3} to 10^{-4} second. The dead time explained the choking of Geiger counters at rates of a few thousand counts per second, when used with low-sensitivity amplifiers. Trost[57] found that the integrated current flowing through a counter tube increased well beyond the "choking rate," as shown in Fig. 30. The conclusion to be drawn from Trost's experiment was that pulses appeared within the dead time which were reduced in amplitude below the detection level of the amplifier. They were then not counted, but contributed a reduced charge per pulse to the flow of current through the tube. Muehlhouse and Friedman,[58] using a sensitive wide-band amplifier, measured counting rates as high as 100,000 per second in a Geiger tube whose resolving time at low rates appeared to be 10,000 per second. The dead time decreased with counting rate above 10,000 per second in such a manner that a constant 40 per cent of the counts were lost at any rate up to 100,000 counts per second.

Baldinger and Huber[59] recently studied the behavior of counters at rates higher than the "Stever dead time." At very high rates almost all pulses fell into the "recovery period," and the average pulse height became a small fraction of normal. These smaller pulses were followed by shorter dead times. The dependence of dead time on pulse height was linear down to pulses of about one-fifth normal amplitude, which was the range covered by the experiment. Increasing the amplifier sensitivity is, therefore, effective in raising the maximum counting rate, but does not materially improve the resolution at low rates.

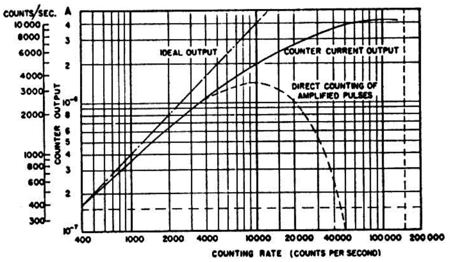

Fig. 30—Counting losses due to dead time. The amplifier responded to pulses as small as half normal amplitude. (See Trost, footnote reference 56.)

Attempts have been made to reduce the dead time by reversing the collecting field immediately after formation of the positive ion sheath so as to return the positive ions to the wire. The recovery time, instead of being governed by the time required for the positive ions to cross the diameter of the counter, would then be reduced to the time required to cover the very small distance from the initial radius of the sheath to the wire. Simpson's[60] original circuit for this purpose applied a high and adjustable negative pulse of a few microseconds duration to the wire. The pulse was derived from a fast one-shot multivibrator, triggered by the amplified initial pulse of the Geiger discharge. Simpson estimated that the improvement in speed of ion collection obtained this way could reduce the dead time by almost a factor of ten.

Other reversing circuits have since been described by Hodson[61] and by Smith[62] but they attributed most of the dead-time reduction which they obtained to limitation of the discharge spread, rather than to positive-ion collection. Before the discharge could propagate the full length of the tube, the wire potential dropped below threshold, bringing the discharge to a stop and leaving the remaining length of the counter still sensitive. Since the rate of spread of the discharge is about 10 centimeters per microsecond, this effect is most readily observed in a long counter. Extremely fast circuitry would be required to limit the discharge spread appreciably in a short counter. Smith estimated that ion collection alone reduced the dead time by only a factor of two, and cautioned against the possibility of interpreting spurious pulses which arise from secondary emission at the wire during the positive ion collection period, as evidence of dead-time reduction.

An effective way to reduce the dead time is to limit the discharge spread along the wire by the use of glass beads. If, for example, the counter wire were divided into two equal lengths by a bead at the center, it would behave as two separate counters connected in parallel. The effective dead time of the combination would then be half the dead time of either section alone. Because the positive-ion sheath is only half as long, normal pulse amplitude must, of course, be only half that of the same counter minus the bead on the wire.

Substituting a bundle of small counters for the equivalent volume of a single large counter will increase the resolution by more than simply the number of counters in the bundle, since each counter of the bundle will itself have a shorter dead time than the single large counter. Multi-element structures of the types illustrated in Figs. 19–23 show similar gains in resolving power. The parallel-plate and wire structure is particularly effective, because the small spacing of individual plates in itself produces a short dead time per element. In open structures, such as the tube of Fig. 21, only a few per cent of the discharges can spread from one wire to another because of the strong absorption of ultraviolet light in fillings of rare gases in combination with polyatomic quenching admixtures. The effect on resolution is almost equivalent, therefore, to operation of independent counters in parallel. If such a tube is filled with simple gases, or the rare gases with halogen admixtures, the discharges spread throughout the entire structure, and the effect of limiting each discharge to a single wire is lost.

BACKGROUND REDUCTION

When measuring weak activities, the ultimate sensitivity of the counting method is controlled by the background count against which the sample activity must be distinguished. This background consists of cosmic radiation, gamma rays from natural radioactivity in the surroundings, and, in many laboratories, stray radiation from near-by accelerators. A rough figure for the cosmic radiation is about 1.5 cosmic rays per minute per square centimeter of horizontal surface at sea level. The larger the background, the more difficult it becomes to detect a small increase in counting rate. For example, if the background is equal to the counting rate being measured, then six times as many counts are needed to achieve a given statistical accuracy compared to the number required in the absence of background. If the ratio of sample count to background is as low as one tenth, then 121 times as many counts are required as in the absence of background. The advantage to be gained by any technique which reduces background is obvious.

In discussing the construction of Geiger counters for beta-ray measurements, consideration was given to designs in which the ratio of sensitive volume to window area was minimized, thereby improving the ratio of beta count to background. It is customary to surround a counter and the sample to be

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[57] A. Trost, "A method for measuring high radiation intensities using a counter tube," *Zeit. für Phys.*, vol. 117, pp. 257–264; 1941.

[58] C. O. Muehlhause and H. Friedman, "Measurement of high intensities with the Geiger-Mueller counter," *Rev. Sci. Instr.*, vol. 17, pp. 506–511; November, 1946.

[59] E. Baldinger and P. Huber, "On the resolving power of self-quenching counter tubes at high rates," *Helv. Phys. Acta*, vol. 20, pp. 470–475; November 6, 1947.

[60] J. A. Simpson, "Reduction of the natural insensitive time in Geiger-Mueller counters," *Phys. Rev.*, vol. 66, pp. 39–47; August, 1944.

[61] A. L. Hodson, "Reduction of insensitive time in Geiger-Mueller counters," *Jour. Sci. Instr.*, vol. 25, pp. 11–13; January, 1948.

[62] P. B. Smith, "Dead-time reduction in self-quenching counters," *Rev. Sci. Instr.*, vol. 19, pp. 453–458; July, 1948.

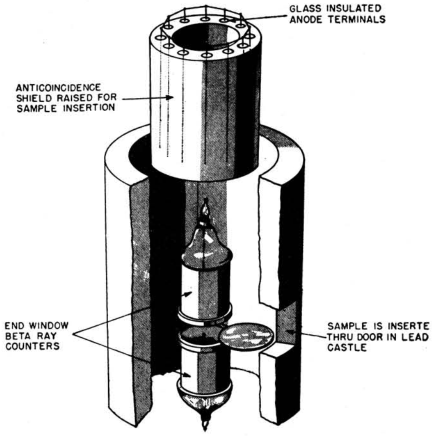

Fig. 31—Schematic arrangement for background reduction.

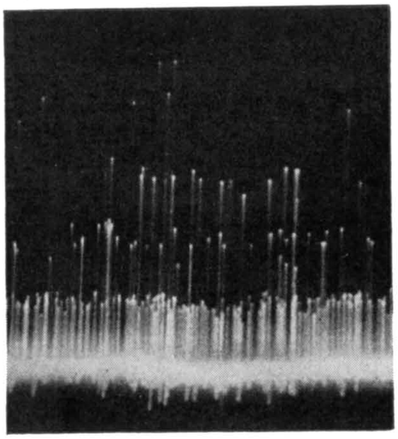

Fig. 32—Variety of pulse amplitudes obtained from tube of Fig. 22.

measured by a lead shield which effectively eliminates the gamma-ray background, but does not stop the penetrating cosmic-ray particles. However, because the efficiency of cosmic-ray particle detection with Geiger counters is close to 100 per cent, it is a simple matter to screen out the counts due to penetrating cosmic-ray particles by anticoincidence circuitry.

Fig. 31 illustrates an arrangement of high geometry for beta-ray detection combined with an anticoincidence shield. Two end-window beta-ray counters are mounted face to face with a sufficient gap between them to accommodate a flat sample. The sample material may be supported on a thin aluminum foil or plastic film which is capable of transmitting almost all the beta rays emitted by the radioactive atoms in the sample. With a small source, this arrangement collects nearly every particle emitted over the entire solid angle or presents what is ordinarily referred to as a 4π geometry. The circuitry is so arranged that single random firings of the two counters are transmitted to the scaling circuit, but coincident pulses, excited by the passage of the same cosmic-ray particle through both tubes, are rejected. The cosmic ray shield is completed by slipping the anticoincidence guard counter down around the two beta counters. The guard counter as illustrated is equivalent to a cylindrical ring of counters connected in parallel. Any coincidence between this shield counter and either of the two beta counters is rejected by the electronic circuit. The net result achieved by this arrangement for rejecting coincidence counts is to reduce the background, after shielding in lead, by still another factor of five, without loss of beta-ray counts. Fig. 31 illustrates a system employing two conventional end-window counters. It is immediately apparent that shallow counters of the type shown in Figs. 26 and 27 are still better suited to anticoincidence counting. If the depth of each Geiger counter is much less than its window diameter, then it is possible to dispense with the outer cylindrical shield and rely entirely on rejection of coincidences between the two beta-ray counters.

Gamma-ray counters of the multiple-element types illustrated in Figs. 19–23 are well suited to the application of anticoincidence counting. Fig. 32 is a photograph showing the variety of pulse amplitudes observed on an oscilloscope with the counter of Fig. 22 exposed to gamma rays. Since the anodes and cathodes are connected in parallel, coincidence pulses on more than one wire appear with double, triple, quadruple, etc., amplitudes, depending on whether two, three, four, etc., wires are fired by the passage of a single particle. The great majority of the pulses are single counts typical of gamma rays. Occasionally, the Compton electron ejected by a gamma ray traverses the fields of two wires, and a few per cent of the discharges spread from one wire to another, leading to double-amplitude counts. Triple-amplitude pulses from gamma rays are very infrequent. On the other hand, all wires whose sensitive regions are cut by the trajectory of a cosmic-ray particle fire in coincidence. The largest pulses are, therefore, produced by a cosmic-ray particle penetrating the tube along a plane through its axis. If the cosmic ray penetrates fewer elements of the tube, pulses of lesser amplitude result. By selecting the proper pulse-amplitude discrimination level, it is possible to reject pulses above a given level so as to eliminate almost all background from penetrating cosmic rays.

Directional Counters

The production of a preferred directional sensitivity in a gamma-ray counter, without the benefit of external shielding by means of lead or other high density absorbers, is rather difficult to achieve in any high degree. Since the efficiency of counting depends on the material of the cathode wall, its thickness, and distribution in the path of the beam, it is possible to construct a tube so as to present a higher counting efficiency to a source in one direction than in others. Also, since gamma rays are detected mainly by virtue of the ejected Compton electrons, which have a predominantly forward distribution, a tube that is responsive to electrons moving in a particular direction should, therefore, be directional in response to the primary gamma rays.

Rajewski[63] described a bimetallic cathode for a gamma-ray counter consisting of two hemicylinders of lead and aluminum. Because of the different efficiencies of the two metals, the counting rate for rays entering lead and leaving aluminum was greater than for rays traveling in the reverse direction. Craggs and his coworkers[64] recently determined the contrast in sensitivity obtainable by such tubes with the aid of a parallel-plate and wire form of counter. Diametrically opposed windows were cut in the glass envelope of the tube at positions orthogonal to the planes of the plates. These windows were covered with aluminum foil 0.002 inch thick. The response of this counter to a collimated beam of gamma rays was 32 per cent lower when the beam passed through the windows than when it was directed perpendicularly to the surfaces of the plates. This experiment indicates the extreme of contrast obtainable in a bimetallic form of directional counter.

The experiments of Stever showed that it was possible to localize the discharge in a Geiger counter by placing glass beads on the anode wire. If the beads were opaque to ultraviolet light, the spreading of the discharge by photoelectric effect in the gas was blocked at the bead. Stever suggested the use of the beaded-wire counter as a directional detector of energetic particles. For example, if the wire were partitioned into three sections by glass beads, a particle traversing the tube in a direction normal to the axis would fire only one section, whereas a particle traversing the counter parallel to the axis would fire all three sections. Since the pulse amplitude developed by the counter is proportional to the length of the discharge along the wire, a circuit which discriminates against smaller pulses arising from the firing of one or two sections rather than all three will register only those counts arising from the triggering of all three sections by a primary particle traveling essentially parallel to the axis of the counter.

Since high-energy gamma rays produce a distribution of recoil electrons with a maximum in the forward direction, a Stever type of beaded-wire counter should have directional properties for gamma-ray detection. However, because of the angular distribution of recoil electrons, the directionality of response is not very pronounced, and the counting rate is corresponding low.

The most satisfactory arrangements for obtaining directional sensitivity with gamma counters are those which simply employ shielding with lead or other high-density absorbers. When the gamma rays are emitted from a point source, it is advantageous to use two counters separated by a lead barrier and coupled to a differential-counting-rate meter.

Photon Counters

The photon counter combines the principle of the photocell with the amplification mechanism of the G-M counter. Rajewski[65] and Locher[66] described the behavior of such

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[63] B. Rajewsky, "The use of the Geiger-Mueller counter in mining," *Zeit. für Phys.*, vol. 120, pp. 627–638; March, 1943.

[64] J. D. Craggs, P. W. Bosley, and A. A. Jaffe, "Some experiments with Geiger-Mueller counters," *Jour. Sci. Instr.*, vol. 25, pp. 67–71; March, 1948.

[65] B. Rajewsky, "On the sensitivity of photon counters," *Phys. Zeit.*, vol. 32, pp. 121–124; February, 1931.

[66] G. L. Locher, "Photoelectric quantum counters for visible and ultraviolet light," part I, *Phys. Rev.*, vol. 43, pp. 525–546; November 15, 1932.

tubes in 1931. Much of the work since then has been confined to ultraviolet counters operating in the region below 3,000 Å, although Locher achieved considerable success in the preparation of blue-sensitive (threshold, 4,000 Å) tubes. So little effort appears to have been expended on the production of photon counters with long-wavelength sensitivities that it is difficult to evaluate their possibilities. Of all detectors, the photon counter has inherently the maximum sensitivity for measuring the photocurrent; i.e., it counts every photoelectron. To date, however, it has not been possible to duplicate in gas-filled tubes the quantum yields obtained with photo surfaces in vacuum in the spectral range from 3,000 to 5,000 Å. Surfaces that are highly photosensitive in vacuo when exposed to visible light are invariably poisoned and desensitized by contact with the gas in a counter. At shorter wavelengths in the ultraviolet, however, quantum efficiencies between 10^{-4} and 10^{-3} counts per quantum are commonly obtained[67] in photon counters. These yields are comparable to those observed for most photosurfaces in vacuum in that region of the spectrum.

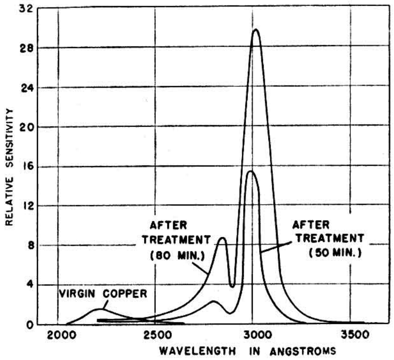

Fig. 33—Ultraviolet sensitivity of activated photon counter tube. (See Scherb, footnote reference 58.)

Locher described many surface coatings and treatments which produced enhanced quantum yields in photon counters operating in the blue and ultraviolet portions of the spectrum. Since Locher's experiments, very little has been published on photon counters. More recently, Scherb[68] described unusual spectral sensitivities obtained by glow-discharging an argon-butane-filled copper-cathode counter at liquid-air temperature. Fig. 33 illustrates the results of this treatment which produced a peak at about 3,000 Å with a quantum yield about 15 times as great as that of the untreated copper surface between 2,000 and 2,500 Å. It seems reasonable to expect that many similar improvements would develop out of research on photon counters if an effort were made to continue such investigations. There are interesting possibilities for the application of such tubes to spectroscopic instruments and in connection with scintillation counting.

CONCLUSION

The writer has limited the contents of this paper to a discussion of Geiger-counter tubes for the detection of cosmic rays, X rays, gamma rays, beta particles, and ultraviolet light. Neutrons, protons, and alpha particles are ordinarily detected by means of proportional counters and pulse ionization chambers, which do not fall within the scope of this paper.[69]

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[67] O. S. Duffendack and W. E. Morriss, "An investigation of the properties and applications of the Geiger-Mueller photoelectron counter," *Jour. Opt. Soc. Amer.*, vol. 32, pp. 8–24; January, 1942.

[68] M. V. Scherb, "Photoelectric effect in self-quenching Geiger-Mueller counters," *Phys. Rev.*, vol. 73, pp. 86–87; January 1, 1948.

[69] The references cited here represent only a small portion of the published literature on Geiger counter tubes.

Microwave Phase Front Measurements for Overwater Paths of 12 and 32 Miles*

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Summary—**This paper presents the results of microwave measurements at a wavelength of 3.2 cm for overwater paths of 12 and 32 miles near Galveston, Texas. Continuous curves of phase and signal strength for a range of transmitter and receiver heights between 10 and 55 feet mean sea level are shown. Comparison of the two radio paths is made, and deviations of the results from those commonly expected for overwater propagation are pointed out.**

I. INTRODUCTION

THE UNUSUAL characteristics of microwave propagation over water at low elevations have been discussed in numerous papers.[1,2] When the air along the radio path used in this study has traveled a considerable distance over water, radio ducts are produced in which microwave signals may be trapped. This trapping produces signal strengths beyond the optical horizon much greater than would occur under standard conditions.

This paper describes the measurement of phase and signal strength as functions of transmitter and receiver heights at a wavelength of 3.2 cm for overwater paths of 12 and 32 miles. It is believed that these are the first microwave vertical phase measurements which have been made for overwater paths.

II. RADIO PATH

The radio path was adjacent to the shoreline along Bolivar Peninsula near Galveston, Texas. A curve in the shoreline permitted completely overwater paths as shown in Fig. 1. The receiving tower was located on a projection of land near the west end of the peninsula.

The transmitting tower was set up at two points on the shoreline at distances of 12.3 and 31.6 miles from the receiver. A few measurements were made for other distances with the transmitter mounted on top of a truck.

III. RECEIVING EQUIPMENT

The receiving equipment measured the phase difference between two antennas spaced 10 feet apart

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[1] P. A. Anderson, K. E. Fitzsimmons, G. M. Grover, and S. T. Stephenson, "Results of low level atmospheric sounding in the southwest and central Pacific oceanic areas," Department of Physics, Washington State College, Report No. 9, February 27, 1945.

[2] Katzin, Martin, Robert W. Buchman, and William Binnian, "Three and nine centimeter propagation in low ocean ducts," PROC. I.R.E., vol. 35, pp. 891–906; September 1, 1947.