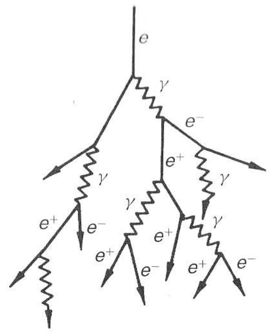


FIGURE 8.11 Formation of an electromagnetic cascade. Note that high-energy electrons (positrons) radiate gamma rays and the gamma rays later convert into electron–positron pairs and so forth.

(or gamma ray) has been transferred to many less energetic electrons (Fig. 8.11).

In another connection we have already used L_{rad} in Eq. (8.19) for multiple scattering; from Table 8.1 we see that in heavy materials scattering will be much more pronounced. Note that multiple scattering is the same for particles of the same momentum. Thus, at low energies a light particle will scatter much more than a heavier particle of the same kinetic energy ($p = \sqrt{2Tm}$). This is clearly seen when observing the tracks of low-energy protons and electrons in an image-forming device; the former ones are, in general, straight, whereas the latter ones suffer multiple scattering through large angles.

8.3. GASEOUS IONIZATION DETECTORS; THE GEIGER COUNTER

8.3.1. General

As mentioned earlier, most particle detectors are based in one form or another on the energy lost by the charged particle due to ionization of the medium it traverses. In a large class of instruments the detecting material is a gas; the ionization potentials are on the order of 10 eV, but on the average, for example in air, the charged particle loses 30 to 35 eV for each electron–ion pair formed.[21] By collecting the free charges that were thus

[21] This is due to additional interactions such as excitation and elastic scattering.

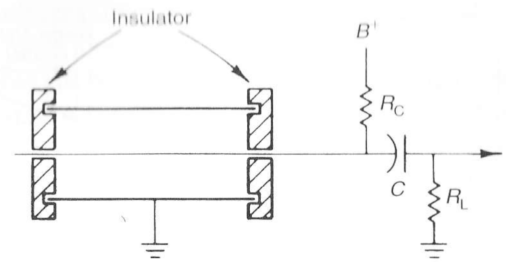


FIGURE 8.12 Diagrammatic arrangement of a cylindrical Geiger counter; the central wire is charged to B^+ through R_C while the cylindrical envelope is held at ground. The output signal appears across R_L.

created, it is possible to obtain an electrical pulse, signaling the passage of the charged particle.

The simplest type of gaseous detector consists of a cylindrical chamber with a wire stretched along its center, as shown in Fig. 8.12. The chamber walls act as the negative electrode, and positive voltage is applied to the central electrode. Under the influence of the electric field, the electrons are collected at the center while the positive ions move toward the walls. It is desirable to collect the free charges before they recombine in the gas; this is mainly a function of the pressure of the gas and of the applied voltage.[22]

If, however, the voltage is sufficiently raised, the electrons gain enough energy to ionize through collision further atoms of the gas, so that there is a significant multiplication of the free charges originally created by the passage of the particle. In Fig. 8.13, Curve 1 gives the number of electron–ion pairs collected as a function of applied voltage when an electron (minimum ionizing) traverses the counter; Curve 2 gives the same data, but for a much more heavily ionizing particle. Thus the ordinate is proportional to the pulse height of the signal that will appear after the coupling capacitor C (in Fig. 8.12).

Referring to Fig. 8.13, we see the following regions of operation of a gaseous counter: in region II the voltage is large enough to collect all the electron–ion pairs, yet not so large as to produce any multiplication. A detector operated in this region is called an *ionization chamber*. As the voltage is further raised, region III is reached, where multiplication of the original free charges takes place through the interaction of the electrons as they move through the gas toward the collecting electrode. However, over

[22] It is also, of course, a function of the specific gas or mixture of gases used.

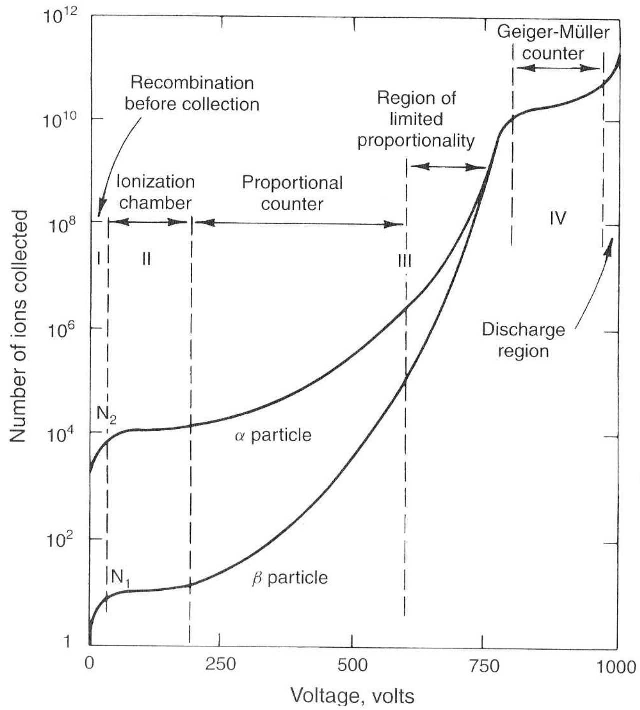


FIGURE 8.13 The number of electron–ion pairs collected when a charged particle traverses a gaseous counter of average size plotted against the voltage applied between the electrodes. Curve 1 is for a minimum ionizing particle, whereas curve 2 refers to a heavily ionizing particle. Note the three possible regions of operation as (a) an ionization counter, (b) a proportional counter, and (c) a Geiger counter.

a considerable range of voltage, the total number of collected electron–ion pairs is fairly proportional to the original ionization caused by the traversal of the charged particle.[23] A detector operated in this region is called a *proportional counter*; it has an advantage over the ionization counter in that the signals are much stronger, achievable gains being on the order of 10^2 to 10^4. Finally, further increase of the high voltage leads to region IV, where very large multiplications are observed, and where the number of collected electron–ion pairs is independent of the original ionization. This is the region of the *Geiger–Müller counter*, which has the great advantage of a very large output pulse, so that its operation is simple and reliable. Indeed,

[23] The proportionality does not have to be a linear function of the applied voltage.

at such high voltages, once a few electron–ion pairs are formed the electrons produce more ionization at such a rapid rate that regenerative action sets in, the whole gas becomes ionized, and a discharge takes place. At that point, the resistance between the central electrode and the chamber wall becomes negligible, and the counter acts as a switch that has been closed between the high-voltage source and ground; this discharges capacitor C through resistor R_L (Fig. 8.12). Since C was charged at B^+ (on the order of 1000 V), very large output signals may be obtained. For example, if the number of electron–ion pairs collected is 10^{10} (as given by Fig. 8.13) and $C = 0.001\ \mu\text{F}$, we obtain

$$V = \frac{Q}{C} = \frac{1.6 \times 10^{-19} \times 10^{10}}{10^{-9}} = 1.6\ \text{V}. \tag{8.37}$$

By scaling this result according to the graphs in the figure, it is easy to appreciate the difficulties involved in the amplification of proportional-counter and ionization-counter signals.

The disadvantages of the Geiger counter are the loss of all information on the ionizing power of the charged particle that traversed the counter, and the long time necessary for restoring the gas to its neutral state after a discharge has taken place. However, the simplicity and good efficiency of the device for single-particle detection have made it a very common nuclear radiation detector.

8.3.2. The Ionization Chamber

The main difficulty with ionization counters is their very low signal output. If they are used, however, in an intense flux of radiation as an integrating device, high signal levels can be reached; in that case the output signal corresponds to the total number of electron–ion pairs formed (per unit time) by the radiation. In this fashion ionization chambers are frequently used for monitoring X-ray radiation or high levels of radioactivity; in such applications they are far superior to Geiger counters, since the rates are so high that a Geiger would be completely jammed.

When an absolute measurement of the created free charges is made, as with an electrometer, ionization chambers may also serve as standards of ionizing radiation. Most commercial instruments, however, amplify the output pulse and are directly calibrated in roentgens (or fractions of roentgens) per hour. For use in the laboratory an ionization counter

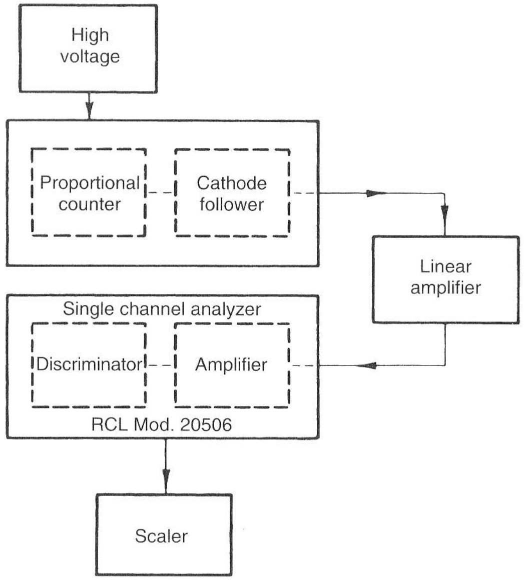


FIGURE 8.16 Block diagram for pulse-height measurements using a proportional counter.

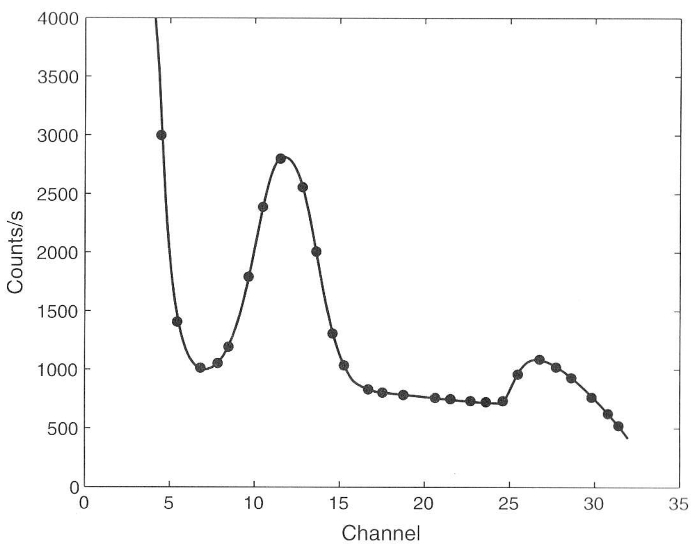


FIGURE 8.17 Pulse-height spectrum of the low-energy gamma radiation from ^{57}Fe as obtained with a commercial proportional counter. The pronounced peak at channel 12 is the 5-keV X-ray while the smaller peak at channel 26 is the 14.4-keV gamma-ray line used in the Mössbauer effect.

8.3.4. The Geiger Counter; Plateau and Dead Time

It has been pointed out in Section 8.3.1 that a gaseous counter operates in the Geiger region when the voltage between electrodes is sufficiently large; that is, the traversal of a charged particle initiates a discharge in the gas, and as a result a pulse appears at the output that is independent of the original ionization. If the voltage is further increased, spontaneous discharges occur, making the device useless as a particle detector.

Because the principle of operation is simple, Geiger counters are simply constructed, the geometry of Fig. 8.12 being typical. For certain applications, the thickness of the walls is an important consideration, and Geiger counters may be built with special thin windows (usually mica of few mg/cm^2). Glass envelopes for Geiger counters are fairly common, and various pressures as well as mixtures of gases are used.

Another important consideration for Geiger counters is the "quenching" of the discharge initiated by the traversal of a charged particle. Until the gas is returned to its neutral state, the passage of a charged particle will not produce an output pulse; this is the period of time during which the counter is "dead." The quenching of the discharge can be achieved through the external circuit (for example, in Fig. 8.12 the charging resistor R_C will introduce such a voltage drop that the discharge will extinguish itself), through the addition of special impurities (such as alcohol) to the gas of the counter, or by both methods used together. The circuitry necessary for the operation of a Geiger counter is also extremely simple. A single stage of amplification and pulse shaping is usually sufficient to drive any scaler.

In order to operate a Geiger counter properly, the high-voltage source must be set in the "plateau" region (Fig. 8.13, region IV), where a similar output is consistently obtained for all charged particles traversing the counter. We may then define the *efficiency* of the detector as the ratio of the number of output pulses over the total flux traversing the counter; since the pulse heights are all equal in the plateau region, we do expect the efficiency to remain constant in that same region. Clearly any particle detector should be operated in a region where the efficiency is "flat" with respect to variation of operating parameters. The efficiency of Geiger counters is 90% or higher for charged particles, but for photons it is much lower, being only on the order of 1–2%.

It is difficult to make absolute efficiency measurements for Geiger counters. A "standard" calibrated source of radioactive material may be used, and the output count compared with the expected flux from a knowledge of the solid angle subtended by the Geiger counter. If the counter is placed at several distances from the source, the consistency of the measurements may also be checked through the $1/r^2$ dependence. However, a *relative* measurement of the efficiency as a function of the high voltage is easy to make; if it yields a *flat plateau*, this is an indication that the detector operates at high efficiency (close to 100%) for the particular type of radiation that is incident. Geiger-counter plateaus are usually a few hundred volts wide and have a small slope, on the order of 1–2% per 100 V.

To determine the plateau, either a radioactive source or the cosmic-ray flux may be used; since this flux is on the order of 10^{-2} particles/cm^2-s, it takes several minutes to accumulate 1000 counts for a counter of average size. As explained in Chapter 10, the emission of radiation is a random process, so that the standard deviation[29] of any measurement is given by the square root of the number of counts, and thus the measurement should be interpreted as

$$1000 \pm 31 = 1000 \times (1 \pm 0.03) \text{ counts}$$

or in common parlance, 1000 counts give 3% statistics. The high voltage should be well stabilized, usually to a few parts in one thousand.

Figure 8.18 gives the plateau found by a student for the RCL[30] type 10104 Geiger counter. A 10-μCi ^{60}Co source was used for the measurements, and the standard deviation at each point is shown by the size of the dot. The plateau begins at 1100 V and is approximately 250 V wide; the discharge region begins at 1400 V.

The slope of the plateau, from Fig. 8.18, is

$$150/3200 = 5\% \text{ per } 100 \text{ V}.$$

Next we turn our attention to the dead time of the Geiger counter already mentioned. Indeed, once a discharge has been initiated, the counter will not register another pulse unless the discharge has extinguished itself, and until, in addition, the counter has "recovered"—that is, returned to a neutral state. During the recovery period, the counter will generate an output pulse, but of a smaller-than-normal amplitude depending on the stage of recovery.

[29]If this measurement is repeated many times, in 68% of the cases we will obtain $\overline{N}-\sigma > N > \overline{N}+\sigma$, where $\overline{N}$ is the average of all measurements. See Chapter 10 for the definition of σ.

[30]Radiation Counter Laboratories, Inc., 512 West Grove Street, Skokie, Ill.

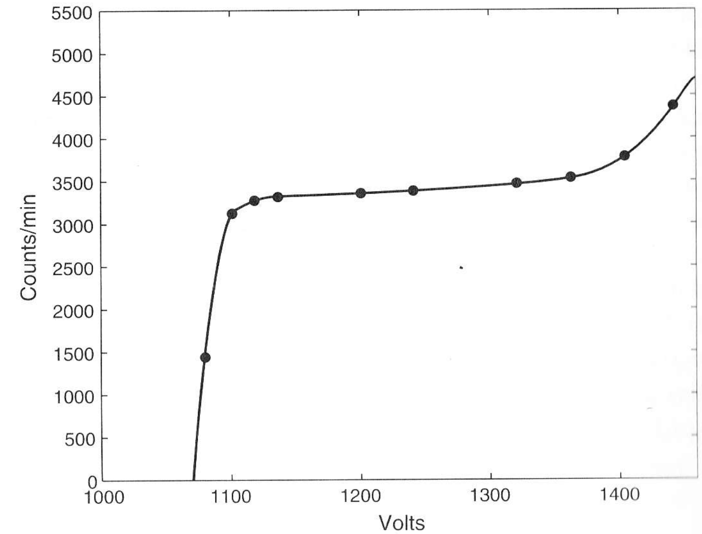
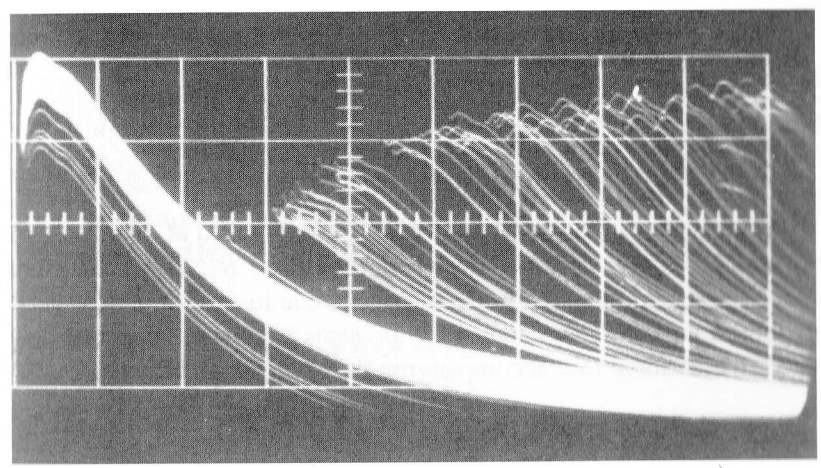


FIGURE 8.18 Plateau curve of a Geiger counter. Note that the plateau region extends for 250 V and has a slope of the order of 5% per 100 V.



Horizontal scale 100 μsec/cm
Vertical scale 5 V/cm

FIGURE 8.19 Multiple-exposure photograph of oscilloscope traces obtained from a Geiger counter exposed to a high flux of radiation. Note the effect of the "dead time" of the counter and the gradual buildup (recovery) of the output pulses.

This phenomenon of recovery can be clearly seen in Fig. 8.19, obtained by a student. The Geiger counter was exposed to a high flux of radiation; the trace of an oscilloscope is triggered when the output pulse appears. The horizontal scale is 100 μs/cm so that the shape of the output pulse and its exponentially decaying tail can be seen in detail. If now a second particle arrives within 1 ms of the previous one, it will appear on the same oscilloscope trace since the scope will not trigger again until the sweep is completed (the screen is 10 cm wide). The picture shown in Fig. 8.19 was obtained by making a multiple exposure of such traces. The correlation of pulse height against delay in arrival time and the exponential dependence of the recovery are clearly noticeable. If we consider that the counter is inoperative until the output is restored to 63% of its original value $(1-1/e)$, the data of Fig. 8.19 give a value for the dead time τ on the order of

$$\tau = 400\ \mu\text{s}. \tag{8.39}$$

Pulses, however, seem to appear after an interval

$$\tau \approx 300\ \mu\text{s}. \tag{8.40}$$

The dead time of a counter may also be obtained by an "operational" technique, such as by measuring the counting loss when the detector is subjected to high flux. If the dead time is τ (s), and the counting rate R (counts/s), the detector is inoperative for a fraction $R\tau$ of a second; the true counting efficiency is then $1 - R\tau$.

Consider two sources S_1 and S_2, which when placed at distances from the counter D_1 and D_2 give a true rate (counts/s) R_1, R_2. The counter, however, registers rates $R_1' < R_1$, $R_2' < R_2$ due to dead-time losses, and when both sources are simultaneously present, it registers $R_{12}' < R_1' + R_2'$ due to the additional loss accompanying the higher flux. Now,

$$R_1' = R_1(1 - R_1'\tau)$$
$$R_2' = R_2(1 - R_2'\tau)$$
$$R_{12}' = (R_1 + R_2)(1 - R_{12}'\tau).$$

We solve by writing

$$\frac{R_{12}'}{1 - R_{12}'\tau} = \frac{R_1'}{1 - R_1'\tau} + \frac{R_2'}{1 - R_2'\tau},$$

which reduces to a quadratic equation in τ with the solution

$$\tau = \frac{1 \pm \sqrt{1 - R_{12}'(R_1' + R_2' - R_{12}')/R_1'R_2'}}{R_{12}'}.$$

This can be expanded in the small quantity $(R_1' + R_2' - R_{12}')$ to give the approximate expression

$$\tau \approx \frac{(R_1' + R_2' - R_{12}')}{2R_1'R_2'}. \tag{8.41}$$

We now apply Eq. (8.41) to data obtained by students with the same counter used for Fig. 8.19. In practice, source S_1 is first brought to the vicinity of the counter and R_1' is obtained, next S_2 is also brought in the area and R_{12}' is obtained, and finally S_1 is removed and R_2' is measured: thus no uncertainties due to source position can arise. They obtain

$$R_1' = 395 \pm 3\ \text{counts/s}$$
$$R_{12}' = 655 \pm 3\ \text{counts/s}$$
$$R_2' = 334 \pm 3\ \text{counts/s},$$

yielding $\tau = 282 \pm 20\ \mu$s, in better agreement with Eq. (8.40) than with Eq. (8.39).

The rather long dead time of the Geiger counter is a serious limitation restricting its use when high counting rates are involved; the ionization counter and proportional counter have dead times several orders of magnitude shorter.

8.4. THE SCINTILLATION COUNTER

8.4.1. General

As we saw, in gaseous-ionization instruments, the electron–ion pairs were directly collected; in the scintillation counter the ionization produced by the passage of a charged particle is detected by the emission of weak scintillations as the excited molecules of the detector return to the ground state. The fact that certain materials emit scintillations when traversed or struck by charged particles has been known for a long time, Rutherford being the first to use a ZnS screen in his alpha particle scattering experiments.