Charged Particle Measurement

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67.1 Introduction

Interaction of Charged Particles with Matter

There are a number of subatomic charged particles that can be detected by their interaction with matter. These include protons (hydrogen nuclei), β particles (fast electrons), α particles (helium nuclei), light ions, heavy ions, and fission fragments. Some of these particles are emitted by natural radioactivity on Earth or originate from space and reach the Earth in the form of cosmic rays; others are due to human activities (nuclear industry, accelerators). The kinetic energy of charged particles is given in units of electron-volts (eV), where 1 eV = 1.6×10^{-19} J. Naturally occurring α and β particles from radioactive decay have energies up to 10 MeV. Ions, such as Cl^+, are accelerated to 35 MeV and higher in beam analysis procedures. Energetic particles that originate from space can have energies up to 10^{12} GeV. Charged particles traversing matter lose kinetic energy until they eventually come to a halt. In the case of electrons, protons, α particles, or light ions, most of this energy is lost through interactions with the electrons of the target. Heavier ions also lose a significant amount of kinetic energy through direct collisions with the nuclei of the constituent atoms. However, for all types of charged particles of concern here, ionization of the target atoms is the dominant mode of excitation of the detection medium. This process is also the main source of radiation damage in biological tissue.

Energy Loss of Protons and Ions

The quantity of energy deposited by an incident energetic charged particle in a detection medium is a function of the atomic mass, A_{med}, the atomic number, Z_{med}, and the density of target atoms that it meets

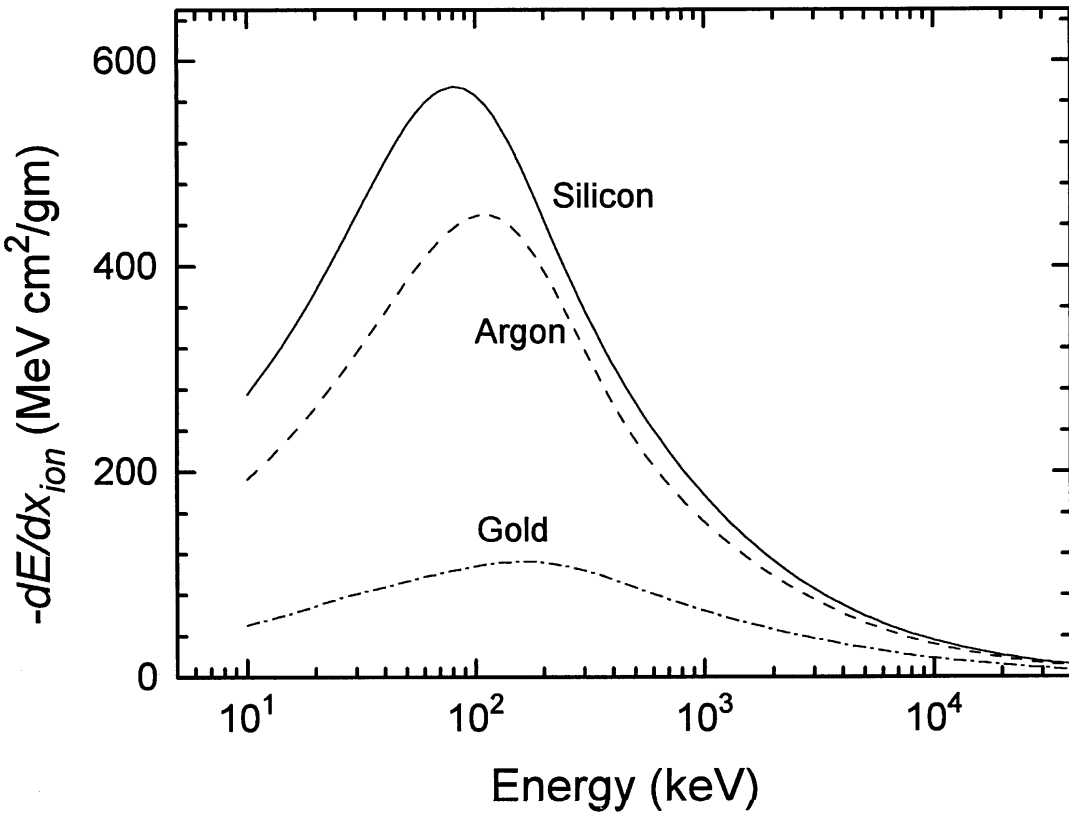

FIGURE 67.1 The electronic energy loss curves for protons in three different absorber elements are shown as a function of kinetic energy. The target element with the lower Z_{med} displays the highest stopping power due to its low average ionizing potential. These curves were obtained using the SRIM computer program. (Reference 2.)

along its path. Hence, the unit of dimension used in this field is the mass thickness, and it is measured most often in units of g cm^{-2}. This is equal to the geometric thickness or path length x, multiplied by the density of the detector volume, ρ. It follows that the rate of energy loss of a particle in the detection volume is $dE/(\rho\, dx)$ and it is given in units of keV (g cm^{-2})$^{-1}$ or MeV (g cm^{-2})$^{-1}$. The energy loss due to ionization is characterized by the Bethe-Bloch equation:

$$-\frac{1}{\rho}\frac{dE}{dx_{ion}} = D\frac{z^2 Z_{med}}{A_{med}}\frac{c^2}{v^2}\left[\ln\frac{2m_0v^2}{I_{med}} - \ln\left(1-\frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right] \quad \text{MeV}\Big/\left(\text{g cm}^{-2}\right)^{-1} \tag{67.1}$$

with D = 0.307 MeV/(g cm^{-2}), c is the velocity of light (3.0×10^8 m s^{-1}) . The incident ion is described by z and v, its charge and velocity, respectively. The atoms of the target are further defined by I_{med} (~16 $Z_{med}^{0.9}$ eV), their mean ionization energy. The energy loss is characterized by a peak at low energy and a minimum at higher energies where a particle of z = 1 is referred to as a minimum ionizing particle (MIP). The energy loss curves of protons in Si, Ar, and Au are shown on Figure 67.1. The energy loss expressed in MeV (g cm^{-2})$^{-1}$ is lower for higher Z_{med} materials, where the ratio Z_{med}/A_{med} becomes less than 0.5 and I_{med} is large. However, when multiplied by the material's density, the energy loss in MeV cm^{-1} shows a reverse trend; it is greater for high Z_{med} materials because they have a high density. The rate of energy loss varies to the second power of the charge z of the incident ion and as the inverse square of its

kinetic energy ($1/v^2$ term). Equation 67.1 holds for protons and α particles of energy above 500 keV and 1 MeV, respectively, in Si where the target is described by an average ionization energy. It is not applicable for ions for which $z > 2$, where stripping must be considered. Ziegler and co-workers [1] give a very useful description of scaling rules that allow the proton energy loss to be scaled to any incident ion and target atoms. They have included these rules in a software package called SRIM [2]. Their empirical relations allows for ion stripping and gives a more exact representation of the energy loss than Equation 67.1 in the case of heavy ions and for low-velocity light ions. Alternatively, one can use published $dE/(\rho\, dx)_{ion}$ plots [3]. Interaction of fast charged particles with the nuclei of the constituent atoms of a target produces an additional contribution to the energy loss, $dE/(\rho\, dx)_{nucl}$, the nuclear stopping power. For protons and α particles, the electronic stopping power dominates by a factor of 1000 over the nuclear stopping power for most energies of interest. For ions, the nuclear stopping power may dominate at low energies (<1 MeV), with its contribution decreasing at higher energies and becoming negligible. The range of a particle, or its path length, is also a very important parameter in the selection of a detector. It is given by:

$$R\left(E_0\right) = \int_0^{E_0} \frac{dE}{dE/dx} \tag{67.2}$$

where dE/dx in this case is the total stopping power $dE/dx_{ion} + dE/dx_{nucl}$. Range–energy curves for various ions in silicon are shown on Figure 67.2.

Energy Loss of Electrons

The case of electron propagation through matter is more complicated. The electron collides with bodies having a mass equal to it (other electrons) or much heavier (nuclei). The collisions cause it to undergo many changes in direction. This "random walk" type of behavior is superimposed on the forward motion of the electron. Along its random path an electron loses energy through ionization in a way similar to ions. At increasing kinetic energy, electrons also lose energy through the emission of X-rays, called bremsstrahlung radiation. In a target constituted of atoms of charge Z_{med} and below a critical energy $E_c \sim 817/Z_{med}$ MeV, electrons lose a greater fraction of their energy through ionization. Above E_c, the energy loss due to bremsstrahlung X-ray emission dominates and is given by:

$$-\frac{1}{\rho}\frac{dE}{dx_{rad}} = B\frac{Z_{med}^{\ 2}\, E}{A}\left(\ln\left(\frac{183}{Z_{med}^{1/3}}\right)+\frac{1}{18}\right)\ \text{MeV}\Big/\left(\text{g cm}^{-2}\right)^{-1} \tag{67.3}$$

where $B = 1.40 \times 10^{-3}$ for E in MeV, and for the molar weight of the target A in grams. Equation 67.3 applies for specified energy ranges, and the interested reader should consult the available literature [4].

The electron range is defined as the distance separating the point of entry in the detection medium to the point where the electron stops. It is much shorter than its actual pathlength and can be approximated by $R(E)$ (Equation 67.4) for E ranging from 0.01 Mev to 3 Mev [5]. Ultimately, the problem of electron propagation through materials has to be addressed using Monte Carlo programs (see References 6 and 7), which follow the individual electron histories to a specified energy or geometrical cutoff.

$$R\left(E\right) = 0.2115 Z_{med}^{\ 0.26} E^n \left(\text{g cm}^{-2}\right) \tag{67.4}$$

$n = 1.265 - 0.0954 \ln (E)$

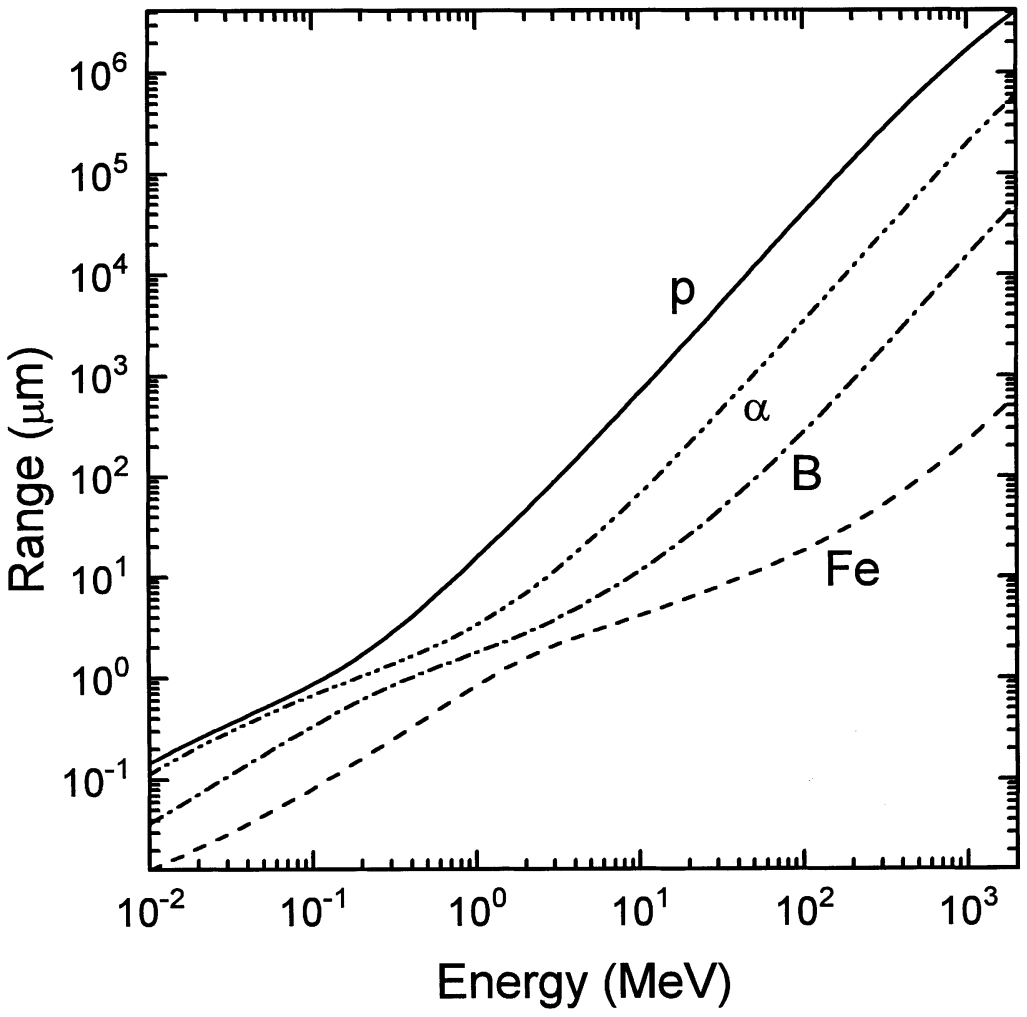

FIGURE 67.2 Ions of widely different masses have widely different ranges in a target element such as silicon. These curves for protons (p), α particles, boron ions (B), and iron (Fe) were obtained using the SRIM computer program. (Reference 2.)

Technologies

The most appropriate detection technique selected depends on the particle under study, its energy, and the type of information sought, such as source activity, position or energy measurement, or particle identification. For all cases reviewed here, except nuclear emulsions, the detection process is active and accompanied by electronic signal processing. Nuclear emulsions permanently record the ionization tracks left by traversing particles and can only be examined after their development. The active technologies include: gas-filled detectors (ionization chambers, proportional counters, Geiger-Müeller counters), scintillators, and solid-state detectors. The active volume consists of a radiation-sensitive material that is raised to an excited state through ionization by the passage of charged particles. For active detectors, this ionization is sensed by the external electronics as an induced charge in the case of gas-based and solid-state detectors, or as visible or near-visible light in the case of scintillators. The sensors described here are the front-ends of complex detection systems.

Nuclear emulsions are a special preparation of photographic emulsion designed to record "tracks" left by ionizing particles as they traverse the emulsion. The emulsion is sensitive up to the time it is processed, and the image is latent for many months or years if the emulsion is cooled. Once processed, the emulsion is a permanent record of the ionizing radiation that traversed it. In a situation where a prompt signal is not required, the nuclear emulsion may be a suitable detector. Its primary advantage is that it is compact, is self-contained, and has high spatial resolution. Since no associated equipment is needed during exposure, it is well suited for remote applications, such as studying cosmic rays and for recording the cumulative exposure to ionizing radiation in space.

Gas-filled detectors were among the first instruments designed for radiation detection. A charged particle passing through a gas-filled container leaves a trail of ionization electrons and ions. With a suitably configured external electric field, the ionization can be used to produce an electrical signal for charged particle detection. Depending on the magnitude of the applied electric field, a variety of ionization phenomena can arise in gases which have been used over the years to develop different types of gaseous charged particle detectors; for example, ionization chambers, proportional counters, Geiger-Müeller counters, spark chambers, etc. Spark chambers are rarely used these days because of electrical noise and limited counting rate ability. The other three devices are used primarily as instruments for radiation protection and monitoring. Their advantage is that they are inexpensive, easy to operate, and are available commercially. In addition, many variants of gas-filled proportional counters have been developed for use in experimental nuclear physics and elementary particle physics. These, however, need to be specifically designed and fabricated for particular applications.

Scintillation counters consist of a scintillation material, a photodetector, and a light guide to link the two. Charged particles crossing the scintillator material deposit energy in the material, which responds by emitting light isotropically. A large fraction of the light can be trapped in the material by internal reflection and directed toward a photodetector, such as a photomultiplier tube. This kind of detector can be used at very high counting rates and can achieve efficiencies approaching 100%. Components for scintillation counters are readily available and it is possible to purchase assembled counters.

Solid-state detectors are large semiconductor diodes made of very high resistivity material and are operated under reverse-bias. The small bandgap in these material ensures that the kinetic energy of the incident charged particle is efficiently converted into an electric signal through the creation of electron-hole pairs. A signal is induced on the metal contacts as the charge carriers drift under the applied electric field present in the depletion region. Their advantages include a fast response, good energy resolution, and compact size.

Table 67.1 presents some radiation sensing applications, the particles under study, and the suggested sensor–system combination. The following subsections present each sensing technology in more detail.

TABLE 67.1 Detection Applications and Suggested Instruments

Detector Type	Typical Applications	Advantages	Shortcomings
Nuclear emulsion	Cosmic ray studies, dosimetry, low statistic (single track) studies	Passive detector, high spatial resolution, unattended operation, particle identification, and energy measurement	No time information, manual scanning, chemical development
Gas-filled counter	Radiation monitoring, dosimetry	Low density, large area at low cost, nuclear and particle physics experiments, realtime particle identification	Needs ultra-pure flammable gases, high voltages required, signals need amplification
Scintillation counter	Energy measurement, particle counting, triggering	Large volumes, flexible shapes, fastest timing, high efficiency	Poor spatial resolution, poor energy resolution
Solid-state detector	Energy measurement, particle identification, position measurement, radiation monitoring, beam analysis techniques	High-energy resolution, compact size	High cost per area, signal needs amplification

67.2 Nuclear Emulsions

Nuclear emulsions are a suspension of silver halide grains, primarily AgBr, in a gelatin medium. The silver halide grains are small, on the order of 0.2 μm to 0.5 μm and constitute about half the volume and 80% of the total weight. The "pellicles" of nuclear emulsion range from 25 μm to 600 μm in thickness and can be as large as 70 cm by 30 cm. The pellicles may be supported on a glass or plastic plate during exposure, or stacked to increase the thickness of the emulsion detector, in which case the pellicles will be placed on a supporting plate as part of processing. If pellicles are stacked for an exposure, then a reference grid is usually printed on the bottom surface of each pellicle to assist in following tracks from one pellicle to the next.

The ionizing radiation crossing a grain of silver halide leaves the grain in an excited state. During development, the excited grains are reduced to elemental silver. The undeveloped grains are washed out during the fixing process. Due to their thickness and to ensure uniform response, a special development process, involving presoaking the emulsions at a reduced temperature, must be used. After development, the nuclear emulsion will have shrunk to about 40% of its original thickness. The thickness is also sensitive to the ambient humidity, and the plates are normally kept in humidity controlled storage (~50% relative humidity). The shrinkage needs to be taken into account for most measurements.

The track image in the emulsion is viewed with a microscope with magnification in the range of 10×10 to 10×100. With the aid of a special microscope, having a calibrated micrometer vertical focus adjustment and a special high-precision stage with calibrated micrometer x- and y-movements, the characteristics of the tracks can be determined and used to identify most particles and to measure their momentum. The dE/dx is measured by determining the grain density along the track. The energy or momentum is determined from the range of the particle or from multiple scattering. Additional information can also be obtained from the density of associated delta rays. These measurements can usually be combined to uniquely determine the charge (but not the sign) and momentum of the particle and the mass in the case of a singly charged particle. The interested reader may find additional information in References 8 through 10.

Nuclear emulsions are currently produced by Ilford Photographic (Ilford Research Laboratory, Ilford Ltd., London, England) and Fuji Photo Film Co. Ltd. (Tokyo, Japan). Several types of emulsion are available with different sensitivities to ionizing radiation.

67.3 Gas-Filled Charged Particle Counters

A gas-filled counter detects the ionization electrons and positive ions produced by a charged particle passing through a gas volume. An electrostatic field established between a pair of electrodes in a gas-filled container causes the electrons to move toward the anode and the ions toward the cathode. The charge movement produces an electrical pulse that can be detected using suitable electronics. A gas-filled counter can operate as an ionization counter, a proportional counter, or a Geiger–Müller counter. Figure 67.3 shows the three operating regions with characteristics determined by the electric field region in which they operate.

Ionization Counter/Chamber: At low fields, the recombination of electron-ion pairs reduces the detector signal, making it electric field dependent. With increasing field, nearly all the charges can be collected before they recombine. In an ionization counter, the signal-to-noise ratio is quite unfavorable, except when used for the detection of heavily ionizing particles (e.g., alpha particles). For radiation monitoring, the device is generally used in integrating mode as an ionization chamber. The current signal in an ionization chamber is proportional to the rate of ionization produced by charged particles interacting in the detector gas volume.

Proportional Counter: At still higher fields, the electrons acquire enough energy between collisions with gas molecules to produce secondary ionization in the gas. The secondary electrons in turn can produce further ionization along their path, leading to an electron avalanche that stops only when all the electrons are collected at the anode. This large increase in the number of primary electrons leads to

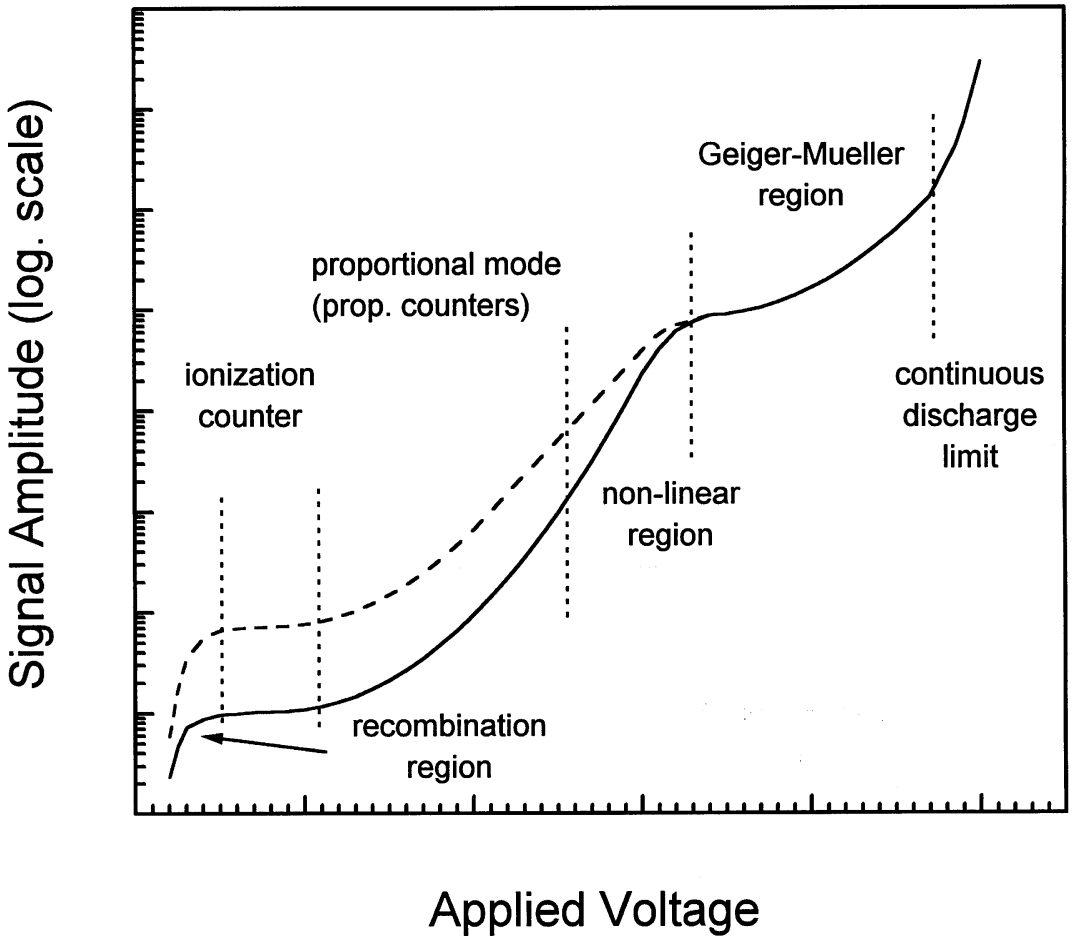

FIGURE 67.3 Typical behavior at atmospheric pressure for a gas-filled counter. Three principal operating regions are identified: ionization region, proportional region, and Geiger-Müller region. The lower curve is for minimum ionizing charged particles and the upper one for heavily ionizing ones. At low operating voltages, the ions and electrons recombine. Continuous discharge occurs at high voltages above the Geiger-Müller region of operation.

a detector signal substantially larger than that produced by a pulse ionization counter. The signal amplitude in a proportional counter is directly proportional to the ionization energy deposited in the gas by the ionizing particle. The proportional counter can detect charged particles without loss of gain at incident particle rates approachnig $10^4\,s^{-1}$ for each millimeter of anode wire length.

Geiger–Müller Counter: Increasing the electric field still further results in increasing loss of proportionality until the counter enters the Geiger-Müller region of operation. In the Geiger-Müller region of operation, a single ionizing event induces an electrical discharge along the entire length of the anode wire. The output pulse amplitude is large and independent of the energy deposited by the ionizing particle in the gas. The Geiger-Müller counter has a relatively long dead time of a few hundred microseconds, and the detector saturates at counting rates above a few thousand particles per second.

Proportional counters have many advantages over ionization chambers and Geiger-Müller counters, both of which are now used mainly as radiation monitors in the laboratory. A gas flow proportional counter is sensitive to the ionization produced in a gas volume by a single charged particle. It can be used for counting charged particles, to measure their energy loss in the gas, and to measure their track coordinates. The proportional counter is more sensitive than an ionization counter because of a built-in

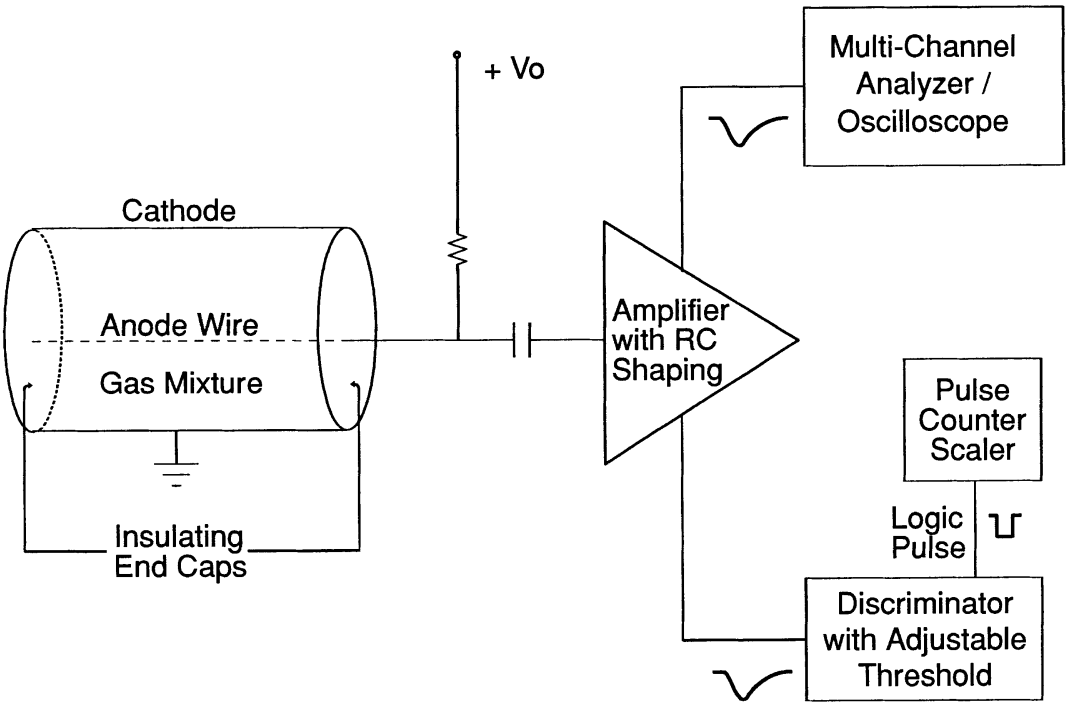

FIGURE 67.4 Schematic diagram of a gas-filled proportional counter and measurement system.

gas multiplication process that amplifies the initial ionization pulse. Because of its relatively short pulse duration, a proportional counter recovers quickly and can count particles at higher rates than a Geiger-Müller counter with its long dead time.

Gas-Filled Proportional Counters

Basic Design and Operating Principle

Figure 67.4 shows the schematic diagram of a gas-filled proportional counter and associated readout electronics. An electrically conducting gas-filled tube serves as the proportional counter cathode. A fine wire 20 to 25 μm in diameter (usually made of gold-plated tungsten) at the center of the tube, supported by insulators on both ends, forms the anode. For reasons of mechanical and electric stability, the anode wire is strung under a tension of several tens of grams, depending on the wire length and operating voltage of the detector. Mylar windows thin enough to allow passage of α and β particles close the gas volume. The cathode is usually kept at ground potential and a positive voltage V_0 is applied to the anode. The electrostatic field is radial with magnitude given by:

$$E = V_0 \Big/ \left(r \ln\left(b/a \right) \right) \tag{67.5}$$

where r is the distance from the central axis, a is the radius of the anode wire, and b is the radius of the tube. The $1/r$ dependence leads to the existence of an intense electric field near the anode wire; for example, at r = 20 μm, the electric field is 25 MV m^{-1} for a 20-μm diameter anode wire held at 1.5 kV within a cathode tube of radius 1 cm. A charged particle passing through the detector ionizes the gas molecules along its path. Under the influence of electric field, the primary ionization electrons start drifting toward the anode. In the strong anode field region a few wire radii from the anode surface, the electrons produce additional ionization along their paths, which leads to the production of an electron

avalanche. The large increase in number of primary electrons is called gas multiplication or gas gain, which becomes significant in the high-field region near the anode. The gas gain is related to the mean free path of the electrons in the gas for secondary ionizing collisions. The electron mean free path is a function of the electric field and the gas pressure. Gas gains as high as 10^8 can be achieved by proper choice of gas mixture and mechanical construction before reaching the limit imposed by electric breakdown in the gas. Most commonly used proportional counter systems have gas gains in the range of 10^4 to 10^6 [4,11,12,].

The voltage pulse observed on the anode is the result of a change in the electrostatic potential energy of the system. Most of the potential energy change is due to the movement of positive ions away from the high anode field region. The contribution of electrons to the total signal is quite small since most of the avalanche electrons traverse only a short distance before being collected by the anode. The fast movement of the ions away from the intense electric field region near the anode produces an initial rapid rise of the signal. About 50% of the pulse height is reached in roughly 0.1% of the total time, followed by a slow logarithmic rise lasting a few hundred microseconds. The signal is proportional to the total amount of ionization produced in the gas; that is, the product of the gas gain and the number of primary electron-ion pairs. The proportional counter energy resolution is determined by statistical fluctuations in the number of ions and by the statistical nature of the gas gain process itself. Deviations from proportionality occur when the space charge density of the positive ion sheath around the anode wire becomes large enough to locally reduce the electric field. The space charge effects become appreciable, depending on the gas gain at counting rates above 10^4 s^{-1} mm^{-1} of anode wire length.

Fill Gases for Proportional Counters

The choice of proportional counter fill gases is dictated by practical considerations. If low gas gain is acceptable, such as for the detection of α particles or heavy ions, both of which produce extremely high specific ionization (initial number of electron-ion pairs produced per cm), almost any gas (even air) can be used. For other particles, one requires a gas that has high specific ionization, high gas gain, low operating voltage, good proportionality, high single particle counting rate ability, and long operating life time. Noble gases such as argon meet the criteria of reasonable gas gain at low operating voltage and high specific ionization. However, the ultraviolet photons produced by excited argon atoms can cause secondary electron emission from cathodes, leading to electrical breakdown at higher operating voltages. The problem can be cured by adding a quenching polyatomic gas with rotational and vibrational levels that can readily absorb the ultraviolet photons. The addition of a quenching gas permits stable high gain operation of proportional chambers. A mixture of 90% argon and 10% methane (CH_4) called P10 is a commonly used proportional counter gas. Several different gas mixtures exist that are capable of achieving proportional gas gains in the neighborhood of 10^6.

The specific ionization for a gas can be calculated from a knowledge of dE/dx_{ion}, the rate of charged particle energy loss in the gas and W the mean energy needed to create a single electron-ion pair. The properties of some common proportional counter gases are shown in Table 67.2. The values of dE/dx_{ion}

TABLE 67.2 Characteristics of Gases Commonly Used in Proportional Counter Gas Mixtures

Gas	W (eV)	dE/dx_{ion} (keV/cm)	Specific Ionization (ion pairs/cm)
Ar	26	2.44	94
Xe	22	6.76	307
CO_2	33	3.01	91
CH_4	28	1.48	53
C_4H_{10}	23	4.50	195

Note: dE/dx_{ion} and specific ionization values are for minimum ionizing charged particles in gas at atmospheric pressure.

and the specific ionization shown in the table are for minimum ionizing charged particle tracks. The specific ionization for a gas mixture is the average specific ionization calculated with partial pressures of the component gases as weights.

The use of organic quenching gases as quenchers in proportional chamber gas mixtures can lead to the formation and deposition of polymers on the electrodes that reduce the operating life of a proportional chamber. To improve chamber lifetime and reduce aging, nonpolymerizing agents such as methylal are frequently added in small quantities to the gas mixture. For proportional counters with sealed gas volumes, the detector performance will degrade due to the contamination of gas in a sealed volume caused by component outgassing. Cleanliness and careful choice of components during fabrication can minimize these effects. The performance of a sealed proportional counter will also degrade with the degradation of the quenching gas component, which can happen when the device is exposed to large fluxes of radiation or after prolonged use. To minimize these problems, proportional counters are often used with external gas supply systems capable of refreshing the gas continuously.

Proportional Counter Operation and Readout

It takes a few hundred microseconds to develop the full voltage pulse in a proportional counter after a leading edge risetime of a few hundred nanoseconds. Even with a gas gain of 10^4 to 10^5, the pulse amplitude is only a few millivolts. Further amplification and shaping is needed to obtain signals suitable for measurements. Often, low-noise amplifiers with built-in *RC* differentiation to shorten the output pulses to 1 μs or less are used (see Figure 67.4). These improve the ability of proportional counters to measure particles at high counting rates without pulse pileup distortions caused by closely spaced pulses overlapping in time. The energy loss of a charged particle in a gas can be measured by measuring the pulse height of the anode signal with an oscilloscope or a multichannel analyzer. For charged particle counting, a discriminator can be used to produce logic pulses that can be counted with a scaler. For coincidence applications, timing resolution of a few nanoseconds is typical for a proportional counter. Good RF shielding and careful electric grounding are essential to maximize the sensitivity of most proportional counters.

The performance of a proportional counter is determined by operating voltage. At lower operating voltages, the best linearity is achieved at the expense of lower gas gain and, consequently, a low signal-to-noise ratio and low efficiency for particle detection. Increasing the voltage leads to larger gain, better signal-to-noise ratio, reduced linearity, faster aging, and susceptibility to electric sparking and damage. In general, the lowest possible anode voltage consistent with achieving good particle detection efficiency is preferred for the operation of proportional counters. This can be accomplished by choosing the operating voltage roughly in the middle of the high-voltage (HV) plateau for the device. On the HV plateau, the counting efficiency of the device remains constant for any variations of anode high voltage [12]. Typical proportional counter operating voltage plateaus are reached in the voltage range of 1.5 kV to 2.5 kV.

Proportional Counters: Advanced Techniques

Many variants of the simple, single wire design have been developed for nuclear physics and particle physics experiments [4,11,12]. Multiwire proportional counters were invented by George Charpak in 1968. In a multiwire proportional chamber, a parallel equidistant row of anode wires is enclosed between two cathode planes. Each anode acts as an independent proportional counter which is read out using suitable electronics. Segments of charged particle tracks can be localized in a multiwire proportional counter in the anode wire plane in a direction perpendicular to the anodes with accuracies on the order of 0.5 mm. A second coordinate along the length of the anode can also be obtained by a measurement of induced signals on a cathode that is segmented in strips in a direction normal to the anode wires. Much more precise particle track coordinate measurements with accuracies of tens of micrometers are possible in another variant called the drift chamber. This is achieved from a knowledge of drift velocities of electrons in the chamber gas as a function of electric field and by measuring the drift time of the ionization electrons to the anode. Complete three-dimensional determination of particle tracks is possible

in a device known as the time projection chamber, which is a combination of a multiwire proportional chamber and a drift chamber. Gas microstrip detectors [13] improve on the high count rate abilities and spatial resolution of a multiwire proportional chamber using closely spaced anode strips that are printed photolithographically on a rigid substrate. Gas microstrip detectors with anode spacings of 200 μm are able to achieve spatial resolution of under 40 μm and count rate abilities in excess of $10^6/(s\ mm^2)$.

Geiger-Müller Counters

Basic Design and Operation

A Geiger-Müller counter [14] is similar in construction to a proportional counter. Operating at electric fields above the proportional region, it is a controlled discharge counter that produces a large output pulse of a few volts for every ionizing event in the gas independent of the amount of energy deposited in the gas. The ultraviolet photons from the electron avalanche in a Geiger-Müller counter induce an electrical discharge along the entire length of the anode wire. Gas mixtures used in Geiger-Müller counters generally contain a noble gas mixed with ethyl alcohol or halogen containing a vapor such as ethyl bromide, which acts as a quencher and eventually stops the discharge. After the discharge, the Geiger-Müller counter has a large dead time on the order of a few hundred microseconds, while the excess ionization is swept out of the chamber, during which it cannot register another pulse. If ethyl alcohol is the quenching agent, the gradual decomposition of molecules causes the counter characteristics to degrade with usage and the counter eventually ceases to function. Counters with a halogen compound used as a quenching agent do not suffer from this defect; however, because halogens are electronegative and capture electrons, such counters suffer from the problem of variable output signal delays. Since the Geiger-Müller counter pulses are several volts high, they require no further amplification for measurement purposes.

Proportional Counter and Geiger-Müller Counter Applications

Proportional counters and Geiger-Müller counters are often used in instruments for radiation protection and monitoring. Depending on the construction, they can be used for both the detection of α and β particles. The simple Geiger-Müller counter is perhaps more commonly used as a radiation monitor because it is easier to use and it has high efficiency, close to 100%. However, because of its relatively long dead time, a Geiger-Müller counter becomes less useful as a monitor in high radiation environments where particle rates exceed a few thousand counts per second. Also, a Geiger-Müller counter provides no energy information. For high counting rate applications or when energy discrimination is needed, it is better to use a proportional counter. Unfortunately, they can be cumbersome to use if an external gas supply is required. Geiger-Müller counters and proportional counter systems can be purchased from many different vendors (see Table 67.3). Prices vary from $100 to $500 for Geiger-Müller and proportional tubes, and up to $2000 for complete systems and accessories (e.g., survey meters, scalers, ratemeters, analyzers, etc).

67.4 Scintillation Counters

Introduction

The use of scintillation light is one of the original methods used to detect charged particles. In 1911, Rutherford used an activated zinc sulfide screen to detect α particles. The flashes of light produced in the screen were counted by a dark-adapted observer. Today, scintillation counters are usually made of either plastic, liquid, or crystal materials, and the resulting signal is detected electronically. The principle of operation of these devices is that the energy deposited by charged particles moving through the scintillator material causes some of the molecules to be raised to an excited state. On returning to the ground state, the molecules emit light. The decay time of the light emitted depends on the fluorescence

TABLE 67.3 List of Manufacturers for Gas-Filled Proportional Counters and Geiger-Müller Tubes

Aptec Engineering Ltd.
East 50 B, Kaldari Road
Concord, Ontario L4K 4N8, Canada
Phone: +1 (905) 660-5373
Fax: +1 (905) 660-9693

Canberra Industries, Inc.
800 Research Parkway
Meriden, CT 06540
Phone: +1 (203) 238-2351
Fax: +1 (203) 235-1347

E G & G Berthold
P.O. Box 100163, D-75312
Bad Wildbad, Germany
Phone: +49 708 1177-140
Fax: +49 708 1177-100

E G & G Ortec
100 Midland Road
Oak Ridge, TN 37831
Phone: +1 (615) 482-4411
Fax: +1 (615) 483-0396

Ludlam Measurements Inc.
P.O. Box 810
501 Oak Street
Sweetwater, TX 79556
Phone: +1 (915) 235-5494
Fax: +1 (915) 235-4672

Oxford Instruments Inc.
601 Oak Ridge Turnpike
P.O. Box 2560
Oak Ridge TN 37831-2560
Phone: +1 (615) 483-8405
Fax: +1 (615) 483-5891

Panasonic
Two Panasonic Way
Cesaucus, NJ 07094
Phone: +1 (201) 392-6044
Fax: +1 (201) 392-4315

TGM Detectors Inc.
160 Bear Hill Road
Waltham, MA 02154-1075
Phone: +1 (617) 890-2090
Fax: +1 (617) 890-4711

Victoreen
6000 Cochran Road
Cleveland, OH 44139
Phone: +1 (216) 248-9300
Fax: +1 (216) 248-9301

time of the scintillator. This can be very short, producing signal pulses as short as a few nanoseconds and thus allowing this type of detector to be used at very high counting rates. The light produced by the scintillator is usually detected using a photomultiplier. An appropriate choice of scintillation medium and detection method can produce a highly effective charged particle counter with an efficiency of essentially 100%.

Scintillation Counters: A Detailed Description

A scintillation counter consists of the scintillation medium, a light detector, and a light guide to transfer the light from one to the other (see Figure 67.5). Information on each of the components of a scintillation detector follows [4].

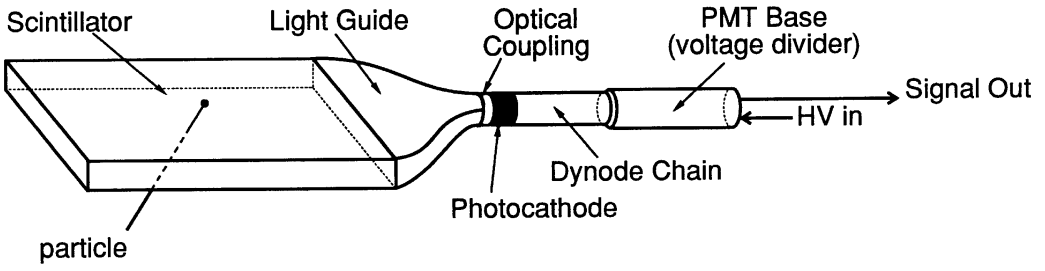

FIGURE 67.5 A typical scintillator system consisting of a scintillation medium, light detector, and light guide.

Scintillation Medium

Plastic or liquid scintillators are usually used for the detection of charged particles. Crystal scintillation media such as sodium iodide or BGO (bismuth germanate) are normally used for photon detection or applications in which energy resolution is important. Plastic detectors are inexpensive and have proved to be a reliable way of detecting charged particles. Large areas can be covered using adjacent sheets of plastic scintillator. Such an array of detectors is known as a hodoscope. Primary light output from a plastic scintillator is at short wavelengths, below 400 nm. Light at these wavelengths has a short attenuation length in the plastic, so wave-shifting dyes are employed to convert the light to longer wavelengths. Thus, a plastic scintillator contains two or more additives such as polystyrene doped with *p*-terphenyl and tetraphenyl-butadiene. Proprietary scintillators are available in a large variety of shapes and sizes from companies such as Bicron Corporation. Plastic scintillators will darken upon exposure to radiation in excess of about 10^3 grays, which will lead to inefficiencies. Liquid scintillation materials, such as toluene, are useful for constructing large volume detectors. Such devices are used in high radiation areas as liquid scintillators are inherently more radiation resistant. It is also possible to replace the liquid if radiation damage occurs. The main problem with this kind of device has been maintaining a leak-proof container and the resulting hazard associated with the toxicity of the liquid.

Light Coupling to Photon Detectors

The light produced in the scintillator is emitted isotropically. A portion of this light is trapped in the scintillator by total internal reflection. For a small detector, it is possible to couple the end of the scintillator directly to a phototube. For larger detectors (exceeding the width of the photodetector), a light guide made of a UV-transparent acrylic plastic is recommended. Acrylic plastic is widely available; Plexiglas by Rohm is one example. Light guides can be made of one piece of shaped plastic but maximum efficiency can be realized using adiabatic (constant area) light guides that minimize light losses. These light guides are quite artistic (see Figure 67.6) and are made from acrylic strips heated and then bent to the appropriate shape. The cut edges are flame polished to produce a smooth surface for good internal reflection. To

FIGURE 67.6 Photograph of adiabatic Plexiglas light guide. (Courtesy of Science and Technology Centre, Carleton University, Ottawa.)

match large scintillators to a small area detecting device, a light guide known as a "Winston cone" [15] is used on the light detector. The shape of the Winston cone minimizes light losses.

Light Detection and Readout

The standard method of detecting light from a scintillator is the use of photomultiplier (PM) tubes. These consist of a light-sensitive photocathode and an amplification stage. The photocathode is a thin layer deposited on the inside of a vacuum tube that has a good probability (>10%) of emitting an electron when struck by a photon. These electrons are electrostatically focused on a secondary electrode (dynode), which is the first element of the amplification structure. The voltage between the photocathode and this first dynode is sufficient to give the electrons enough energy to eject two to four electrons from the dynode. This process is continued through a series of dynodes resulting in a large gain, up to 10^8 in a tube with 14 dynodes. The output pulse is read out from a connection to the anode or the last dynode. The photomultiplier has connection pins corresponding to each dynode. Voltages are supplied to these via a resistive divider network contained in a "base" or "divider." The base requires one HV input and provides one or two signal outputs. Details of divider networks are available from PM tube manufacturers. Further information on the operation of phototubes can be found in Reference [16].

In operation, PM tubes are sensitive to magnetic fields and it is usually necessary to provide magnetic shielding. A tube of a single layer of mu-metal is often sufficient to shield the PM tube from the Earth's magnetic field. For applications where there are higher ambient fields, a shield of layered tubes can be used consisting of two mu-metal shields and up to two soft iron shields. They should extend approximately one tube diameter beyond the PM tube. In applications where an axial field is unavoidable, a bucking coil can be inserted between the two iron layers. A suitable choice of coil current can counteract the axial field.

Scintillator Detector Construction

Assembly of scintillators, light guides, and PM tubes is usually done with an optical cement. It is important in the preparation of the adhesive to remove air bubbles which would scatter the light. It is also possible to make a demountable joint using optical grease or vacuum grease and a mechanical fixture. Such a joint can be used to simplify the replacement of phototubes. Light levels produced in the scintillator are extremely low; therefore, detector assemblies must be enclosed in light-tight envelopes. For plastic scintillators, this is most easily arranged by wrapping with aluminum foil and protecting the foil with black plastic sheets held in place with black adhesive tape. In large systems of counters, it is useful to install LEDs in each scintillator to monitor the operation of the counter. A system for powering the LED with a short duration pulse allows a test of the counter and readout system.

Components for scintillator systems can be purchased from many manufacturers, some of which are listed at the end of this section. Prices vary widely, depending on both the details of the detector and the quantity of components ordered. Typical prices would be \$600 for a piece of scintillator 0.5 cm × 45 cm × 60 cm, \$200 for a voltage divider and \$500 to \$1200 for a 12-stage, 5-cm diameter phototube. Liquid scintillators are available for \$145 per liter. Prices are in U.S. dollars. The cost of custom light guides is dominated by the available labor rate. There are some suppliers (such as Bicron) that will provide complete custom detectors consisting of scintillator, light guide, PM tube, and divider.

Operating Information

A minimum ionizing particle crossing a 1-cm thick scintillator will liberate about 10^4 photons. With typical scintillators and light guides, about 10% of these will reach the photocathode. The efficiencies of photocathodes to produce photo-electrons is usually greater than 10%. Given PM tube gains of 10^8, this leads to 10^{10} electrons at the anode, allowing analog pulses of about a volt to be produced. The pulses typically have a rise time of about 1 ns and a fall time of 5 ns. The trailing edge of the pulses can be shortened to approximately 2 ns by attaching a short grounded line to the output (clip line). The anode outputs are normally connected to a discriminator that produces a standard digital pulse for all analog

pulses exceeding a fixed threshold voltage. More sophisticated circuits, such as constant fraction discriminators, can be used for best timing resolution. Using these devices along with a scintillator geometry that provides good light ouput, a timing resolution of the order of 300 ps (1σ) can be achieved. The excellent signal characteristics of scintillation counters allow them to count efficiently at rates exceeding 10 MHz.

Background counts in a scintillator are caused by cosmic rays and noise in the tube. An average rate from cosmic rays is 1 min^{-1} cm^{-2} sr^{-1}. Tube noise tends to have a lower amplitude than pulses resulting from the scintillator and will have a rate dependent on the choice of threshold. A counter should be checked to see if its count rate is consistent with cosmic ray backgrounds. High count rates are indicative of a light leak, which can be detected by shining a flashlight on the counter in a darkened room. Diligent use of aluminum foil and black tape will fix the leaks. In applications measuring particles that are energetic enough to pass through a counter, system noise can be reduced by using two layers of scintillator and putting their signals in coincidence. Noise can also be minimized by optimal setting of the tube HV and discriminator threshold. If the discriminator threshold is too low, then a large number of tube noise pulses are picked up.

Advanced Techniques

A plastic scintillation counter hodoscope can also be used to obtain position information. The spatial resolution of such a device is limited by the size of the individual detectors. For example, thin finger-shaped counters can be used for measuring beam profiles. Larger "paddles" 10 or 20 cm wide can be used to cover large areas. It is also possible to measure impact position along a counter using phototubes at both ends of a long scintillator and measuring the difference in arrival time of the pulses at the two tubes. Higher precision spatial resolution is possible using scintillating fibers with diameters of around 1 mm. Such a device has a large number of channels and requires segmented cathode phototubes or solid-state readout devices. One such device is the VLPC (visible light photon counter), which is a produced by Rockwell International and is a development from a solid-state photomultiplier. To keep noise low, VLPCs are used at cryogenic temperatures.

List of Manufacturers

Table 67.4 shows a selection of potential suppliers of components for scintillator systems.

67.5 Solid-State Detectors

Solid-state detectors have proved to be very versatile in the detection of charged particles. They have been particularly useful for energy measurements of α and β particles, light and heavy ions, and fission fragments in applications that include nuclear spectroscopy, radionuclide identification both in the environment and laboratory, dosimetry, radiation level monitoring, and non-destructive testing using particle beam techniques. In high-energy physics, solid-state detectors are used mainly as high-precision tracking detectors in a particle counting mode. Most of the devices used in all these applications are based on silicon technology except for energy measurements of β particles (>250 keV), where germanium-based detectors are also used.

Signal Generation

A charged particle moving through a semiconductor crystal loses energy according to the stopping processes described previously (Equation 67.1). The energy lost is spent promoting electrons from the valence band to the conduction band of the crystal. This leaves free electrons in the conduction band and free holes in the valence band. Under the action of an electric field, the free electrons and holes drift in opposite directions and give rise to an electrical current that can be sensed by external electronics.

TABLE 67.4 List of Manufacturers for Scintillator System Components

	Scintillator	Bases/Dividers	Phototubes	Systems
Bicron	x	x		x
DEP scientific	x			
Hamamatsu		x	x	
Philips		x	x	
pol. hi. tech.	x			
Burle			x	
Thorn E.M.I.		x	x	x

Bicron
12345 Kinsman Road
Newbury, OH, 44065-9677
Phone: +1 (216) 564-2251
Fax: +1 (216) 564-8047

Hamamatsu Photonics
325-6, Sunayama-cho
Hamamatsu City, 430, Japan
Phone: +81 53-452-2141
Fax: +81 53-456-7889

Thorn EMI
Bury Street
Ruislip, Middlesex, HA4 7TA, U.K.
Phone: +44 1895 630771
Fax: +44 1895 635953

Burle Industries
100 New Holland Avenue
Lancaster, PA 17601-5688
Phone: +1 (717)-295-6000
Fax: +1 (717)-295-6096

Philips Photonics
100 Providence Pike
Slatersville, RI 02876
Phone: +1 (401)-762-3800
Fax: +1 (401) 767-4493

DEP Scientific
P.O. Box 60
9300 AB Roden
The Netherlands
Phone: 3150-5018808
Fax: 3150-5013510

pol. hi. tech
S. p. Turananse
Km 44,000
67061 Carsolo (AQ) – Italy
Phone: (0863) 997798
Fax: (0863) 995868

The amount of charge produced is very small and the semiconductor must be depleted of majority carriers in order for the signal to be measurable. This is accomplished using a diode structure operated with a reverse-bias voltage. A profile of a "typical" diode detector is given in Figure 67.7. The size of the active region of the detector, the depletion region, is determined by the reverse bias applied and the residual fixed charges. In the case where the material has a very high resistivity (~500 Ωcm or more), the built-in field of the junction can be sufficient to generate a useful depletion layer without any reverse bias.

For a quantity of energy E_0 deposited through electronic interactions, the number of free electron-hole pairs created is $N_p = (E_0)/\varepsilon$, where ε is the average energy to produce one pair, a characteristic of the semiconductor, similar to the W value for gas detectors. Typical values of ε are small, 3.62 eV for Si at 300 K and 2.96 eV for Ge at 77 K. The variance of the number of pairs created is FN_p, where F is the Fano factor [17], which is of the order of 0.1 for Ge and Si. Hence, semiconductor materials are very efficient in converting radiation energy to an electric signal and the pulse-to-pulse variation in the signal size is smaller than predicted by Poisson statistics, where $F = 1$. When all the charge carriers are collected (i.e., the electrons reach the anode side while the holes reach the cathode side), a total of N_p electrons are available to the front end-electronics for amplification and shaping.

Categories of Detector

Device Details

Commercial solid-state detectors (i.e., silicon or germanium devices) are available from a number of manufacturers (see Table 67.5). The following silicon devices are available: silicon surface barrier detectors (SSBD), ion-implanted silicon detectors, diffused junction silicon detectors, *pin* photodiodes, and lithium drifted silicon detectors (Si(Li)). Some of the manufacturers rename the different types using their own

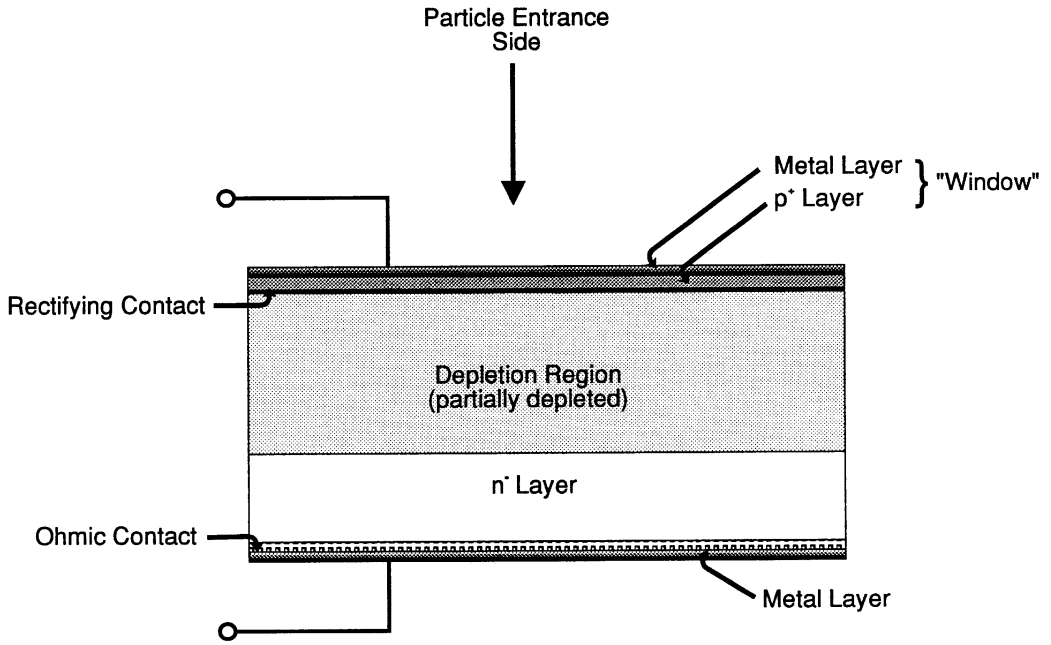

FIGURE 67.7 A solid-state diode detector consists of a thin current blocking layer, a sensitive volume of high resistivity material, and a back ohmic contact. A near uniform field may be established in the sensitive volume.

TABLE 67.5 Device Details

Type	Area (mm^2)	Sensitive thickness (μm)	Dead Layers* (nm)	Particles detected	Prices 1996 US$	Manufacturers
SSBD	10–1000	10–5000	80 225 (back)	p, α, β light and heavy ions	400 to 6000	a b c d
Si, ion implanted	Up to 3000	100–1000	50	p, α, β light and heavy ions	300 to 3000	a b c d
Si pin photodiode	1–900	150–400	100	p, α, β light and heavy ions	10 to 300	e f g h
Si(Li)	25–200	to 5000	1000 Be +200 Si	β, 0.3–3 MeV	~7500	a b c d
HPGe	75–800	to 10000	2500 Be +300 Si	β, 0.3–3 MeV	~9000	a b c d
Silicon strip	See manufacturer for details					c d g i

Note: * Values in nm Si unless stated otherwise.

a. EG&G Ortec (U.S.A.), b. Oxford Instruments Inc. (U.S.A.), c. Eurysis Mesures (France), d. Canberra (Australia), e. EG&G Optoelectronics (Canada), f. Silonex Inc. (Canada), g. Hamamatsu Photonics K.K. (Japan), h. Centronic Inc. (U.S.A.), i. VTT Electronics (Finland).

brand names. The first three types actually lend themselves to nearly the same applications: ion detection. Si(Li) detectors are mostly used for soft X-ray detection, but can also be used for full energy measurement of β particles from 250 keV to 3 MeV. Germanium devices are available as lithium-drifted germanium detectors (Ge(Li)) and high-purity germanium detectors (HPGe). As with the Si(Li) detector, the primary function of germanium detectors is for photon detection but they can also be used to detect β particles. Solid-state detectors are either *pn* or *pin* diodes. Silicon devices fabricated from a starting material of about 500 Ωcm (i.e., ion-implanted Si and diffused junction Si) have the *pn* structure. The SSBD, also made from Si of a few 100's Ωcm, is in fact a hybrid of Schottky junction and *pn* junction due to its

gold-on-*n* type Si interface as well as "*p*-like" surface defects introduced during manufacture. Devices that have a bulk resistivity in excess of 1 kΩcm, whether it is due to a high-resistivity starting material (such as is used for pin Si and HPGe) or compensated material (Si(Li) and Ge(Li)), are *pin* junctions.

Many aspects dictate the choice of a detector for a given application. To measure the full energy of highly ionizing particles, it is important to keep the surface dead layer of the detector as thin as possible to limit the loss of undetected energy. The dead layer is the combination of the entrance metal electrode and the underlying, radiation insensitive, heavily doped top Si layer (usually *p*-type). The required depletion region thickness is determined by the range in Si of the particles of interest. A sufficiently wide depletion region is required for full energy measurements of ions, or to obtain a large signal in the case of energetic particles, such as minimum ionizing particles, which traverses the whole detector without stopping. Energy measurements of β particles often require an active volume that is larger than can be achieved with a standard *p*-*n* junction and so Ge(Li), Si(Li) or HPGe detectors are used. Varnish-coated detectors can be obtained to withstand exposures to rugged environments. Bakeable devices, which allow partial recovery from damage, or inexpensive and replaceable photodiodes can be used in situations of heavy radiation damage. For the detection of heavy ions, devices that can be operated at high electric fields (>15 kV/cm) can be used to overcome recombination effects. One of the most widely used Si detectors is the SSBD. It offers a thin entrance window of less than 100 nm. The diffused junction is the original type of Si detector and it has a rather thick dead layer of 250 nm Si. It is still useful in applications that require a light-insensitive device or for particle physics applications. The implanted junction Si detector results from the implantation of boron ions in an *n*-type Si wafer. It is the most recent addition to commercial Si detectors and it offers a thinner entrance window (less than 50 nm) and a larger surface area than SSBD (see Table 67.5). All these devices can be operated in either partially or fully depleted mode. The thickness of the back dead layer is only relevant to fully depleted, transmission type detectors for energy loss (ΔE) measurements. Recently, high-quality, inexpensive Si *pin* diodes for visible and UV photon detection have been found to be suitable replacements for SSBD in many applications. The thickness of the dead layer is 100 nm, twice that of ion implanted Si detectors, and the resisitivity is as high as 2 to 8 kΩcm for the more expensive versions.

Detector Systems

Three practical systems of increasing sophistication are considered next. The first setup, depicted in Figure 67.8, is used to measure the energy spectrum and the rate of incoming charged particles. One

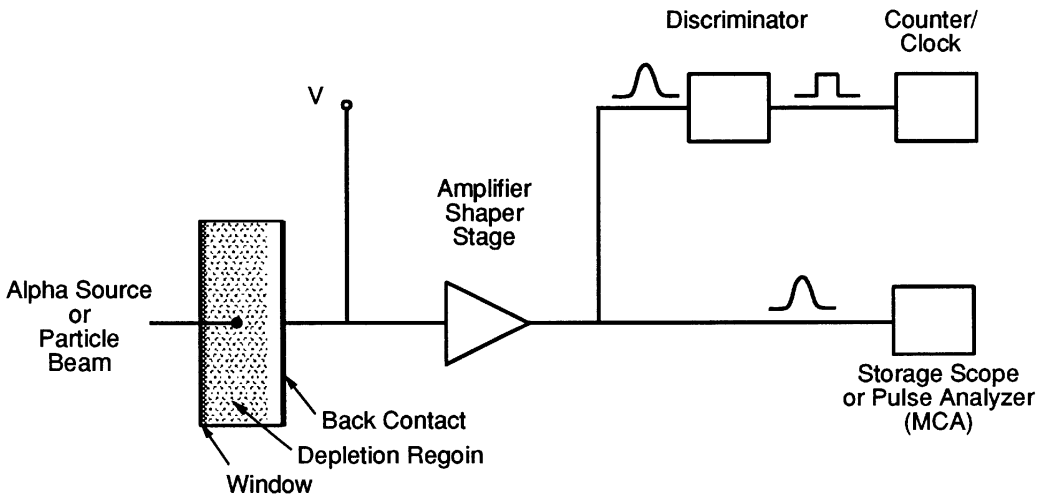

FIGURE 67.8 Using a pulse counter, this simple setup is used to measure the activity of a radioactive sample or the intensity of an accelerator beam. With the addition of a storage oscilloscope or an MCA (multichannel analyzer), the energy deposited in the detector by each incoming charged particle may be measured.

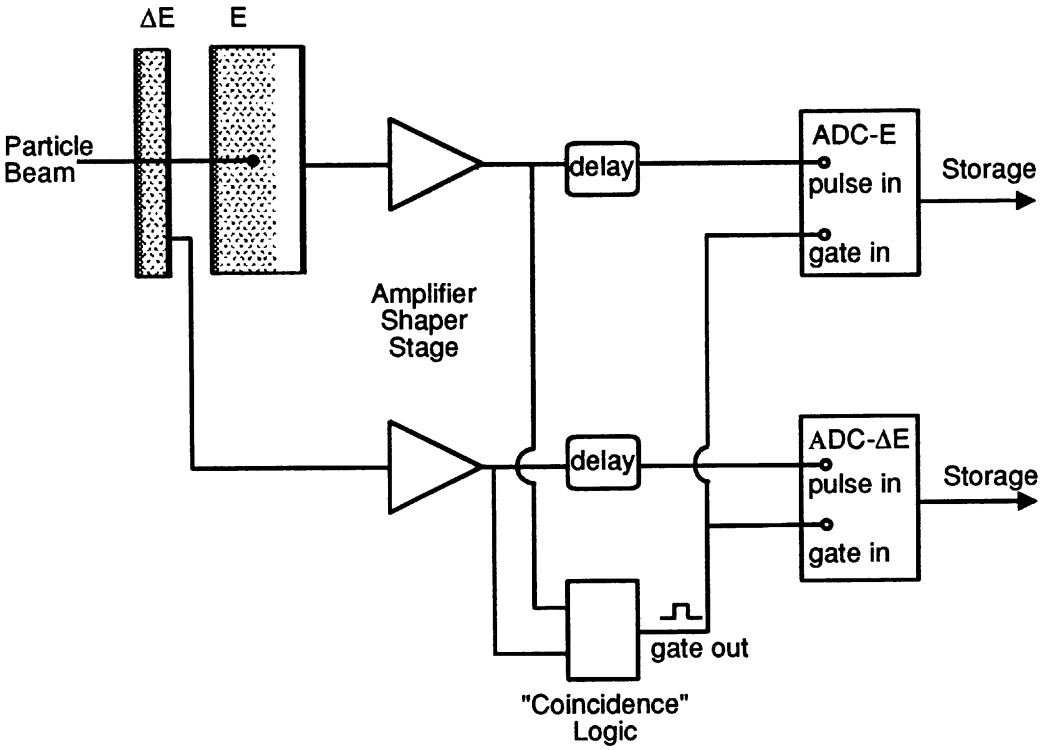

FIGURE 67.9 Knowledge of the amount of energy deposited in a transmission-type detector (ΔE) positioned in line with a full energy measuring detector (E) allows the identification of a particle due to the unique nature of dE/dx and E combination.

possible application is the measurement of the α activity from a natural source or from a wipe test sample. This simple count rate measurement requires a *pn* silicon detector or photodiode, a discriminator, and a pulse counter. By adding a pulse analyzer, called a multichannel analyzer (MCA in Figure 67.8), the same system can be used to record the energy of the α particles or the full energy of light ions, such as those encountered at an accelerator site where beam analysis of materials is performed. In this case, the suggested detector is a good quality SSBD or an ion-implanted detector with a thin window and operated at a voltage sufficient to generate a depletion region at least as wide as the range of the ions of interest. The second setup (Figure 67.9) shows a thin transmission type (ΔE) detector (open front and back), in front of a thick, fully stopping, (E) detector. This configuration is called a ΔE-E telescope and it supplies a simultaneous measure of the energy loss and the full energy of particles going through both devices. This information then uniquely identifies the particle. Finally, Figure 67.10 presents a position-sensitive silicon strip detector for which the localization of a particle hit to better than 5 μm in one dimension is possible [18]. Such a detector is used in particle physics experiments. In many applications, combinations with other detector types, such as scintillators, are also possible.

Detectors with sensitive thicknesses of 100 μm to 300 μm are used in many nuclear spectroscopy and high-energy physics applications. For typical values of applied voltages, full electron collection occurs in less than 10 ns, while hole collection takes less than 20 ns. The amount of charge in a pulse is very small, of the order of 1.5 (10^6) e for the full energy of an α particle and 100 e per μm of path in silicon of a minimum ionizing particle. Depending on the application, the signal processing electronics can be optimized for low noise or fast response. In spectroscopy applications, where precise measurement of the total charge is important, one uses low noise, charge integrating preamplifiers, which offer output gains of the order of 1 mV fC^{-1}. The preamplifiers are optimized for specific ranges of detector capacitance. For detectors of 5 pF and smaller, noise values of less than 1 keV (equivalent energy loss signal in Si)

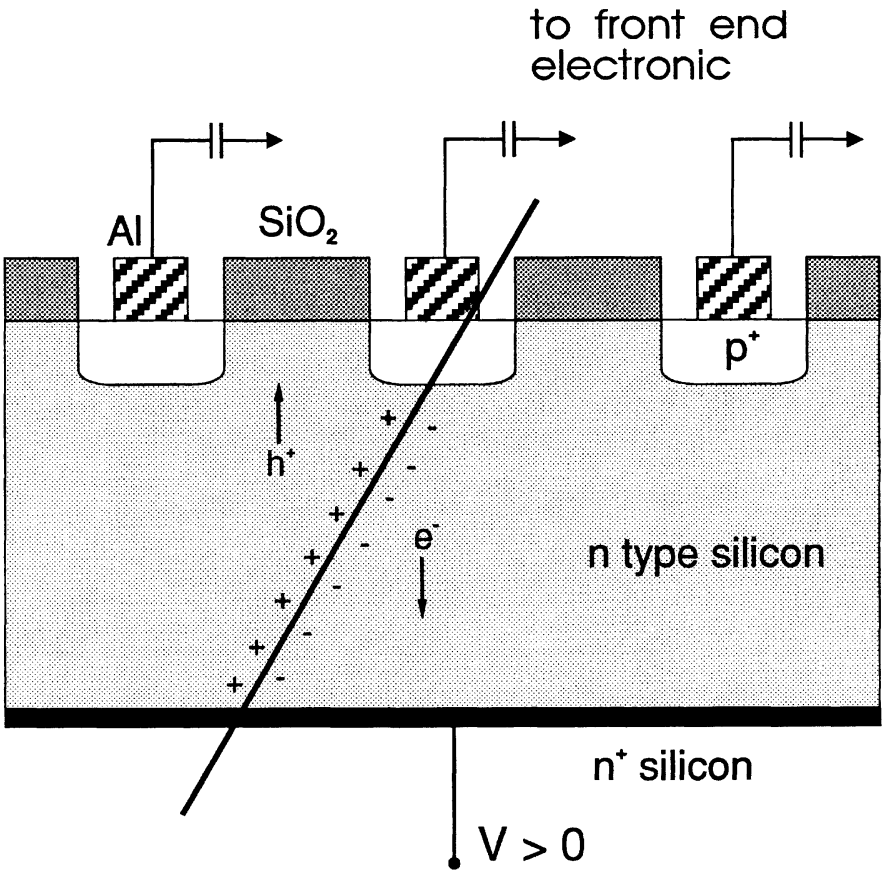

FIGURE 67.10 A silicon strip detector, such as the one depicted here, can be used to localize the hit position of a minimum ionizing particle.

can be achieved. In the case of preamplifiers optimized for larger detector capacitances (200 to 1000 pF), the noise increases with a slope of ~0.02 keV pF^{-1}. Preamplifiers produce a "step" pulse with an amplitude proportional to the input signal charge. The rise time of the pulse varies with the detector capacitance, from 5 ns to 10 ns for <10 pF to 100 ns for 1000 pF. The pulse decay time is determined by internal circuit components and usually falls in the range of 50 μs to 300 μs. The signal is further amplified and shaped using an integrating-differentiating amplifier to provide a pulse of gaussian shape whose width is of the order of 1 μs. This pulse duration limits the counting rate to much less than 10^5 cps before an unreasonably high counting deadtime is encountered. In high-energy physics experiments, the signal processing electronics coupled to position-sensitive detectors are optimized for a high counting rate capability and good timing resolution. Silicon integrated circuits containing a large number of amplifiers are specially designed for such applications. The individual amplifiers provide large output gain (15 mV fC^{-1}) and output pulses whose width can be as small as 20 ns (baseline to baseline), at the cost of an increase in noise (6 keV Si-equivalent). Count rates near 10^6 cps for every detection channel can be achieved with such systems.

Plasma Effects and Pulse Height Defect

Under some conditions, one may observe a loss in proportionality between the energy lost by the particle crossing the detector and the signal. This is called the pulse height deficit (PHD) and it is the sum of

three components: E_W, E_N, and E_R, where E_W is the energy lost in the window or dead layer of the detector and E_N is the energy lost to nuclear scattering (nonionizing). The third term, E_R, is harder to define and is due to a deficit in the charge collection. Ions heavier than the proton create a plasma with a charge density as high as 10^{19} e^-/cm^3 which shields the charge from the collecting field and causes charge loss through electron-hole recombination in the plasma to occur. The PHD increases roughly with the particle mass and energy, and ranges from 1% to 3% for ions such as oxygen at 20 MeV.

New Structures

Modern silicon processing technologies allow the design of intricate structures which find applications in charged particle detection, particularly in high-energy physics experiments. These include position sensitive detectors, with strip electrodes or pixel segmentation, and large-volume silicon drift chambers. Front-end electronics can also be fabricated on the same wafer as the detecting structure itself. Close coupling provides noise reduction. The reader should be aware that new materials, such as GaAs, CVD diamond, natural diamond, cadmium telluride, HgI_2, and hydrogenated amorphous silicon, are being used in prototype detectors. These are beyond the scope of this chapter.

Manufacturers and Prices

A list of typical devices and pricing for each category of solid-state detector is given in Table 67.5. The names of some manufacturers are given but the interested reader is also encouraged to consider other sources.

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