SECTION 6: Detectors

The evolution of nuclear science and technology has been strongly dependent on advances in the design of devices to detect the various forms and energies of nuclear radiation. These vary from rudimentary detectors such as Geiger counters to high resolution devices based upon semiconductor materials. The stopping mechanisms that characterize charged particles, gamma rays and neutrons impose different constraints on the construction of detectors for each type of particle. In addition, the specific application for which a detector is to be used often defines its properties. For example, does one only want to detect the presence of radiation, in which case the detector can be quite simple? If the type of radiation must be identified or if very high energy resolution is required, more sophisticated detectors are required. In this section the types of detectors employed for charged particles, gamma rays and neutrons are described.

Charged Particle Detectors

The two most common approaches to charged-particle detection involve either gas detectors or solid-state detectors. Scintillators – discussed along with gamma-ray detection – and magnetic devices – which will not be discussed here – are also applied to many experimental conditions.

- Gas detectors

The basic principle upon which gas detectors operate is illustrated in Fig. 6.1. A voltage $U_0$ is applied to a pair of electrodes inside a chamber filled with gas; e.g. hydrocarbons. When an ionizing particle passes through the gas, the free electrons are collected at the positive electrode and the positive ions drift toward the negative electrode, thereby creating a current $I$ that passes through a resistance $R$ and producing a measureable voltage pulse $U$. This pulse is then collected over a time $t$ and the pulse height $U(t)$ serves as a measure of the degree of ionization in the gas. It takes 20-30 eV to produce an ion pair in most gases. Thus the signal is related to the number of ion pairs produced, which is related to the energy and type of the particle.

![Fig. 6.1 Schematic drawing of a gas detector in which an ionizing particle passes through the detector gas to which a voltage $U_0$ has been applied to two electrodes. The current collected at the electrodes produces a voltage $U$ when passed through a resistor $R$ that is collected in the circuit over a time $U(t)$.](image)
Gas detectors operate in several different modes, depending on the voltage $U_0$ that is applied. Each mode has specific experimental applications. As shown in Fig 6.2, these modes include:

1. Ionization Chambers
2. Proportional Counters
3. Avalanche detectors
4. Geiger-Muller counters
5. Spark detectors

Fig. 6.2 Signal voltage $U$ as a function of applied voltage $U_0$.

The gas detector response depends on the gas amplification factor $M$,

$$M = \frac{n}{n_0} = \frac{\int \alpha(x) dx}{1 - \gamma(e^{\int \alpha(x) dx} - 1)}$$

(Eq. 6.1)

The exponential factor in Eq. 6.1 is given by

$$\frac{\alpha}{P} = f\left(\frac{E}{P}\right),$$

Where $E$ is the reduced electric field created by the voltage $V$, divided by the electrode separation distance $d$, $E = V/d$, and $P$ is the gas pressure. Thus if $\alpha(x)$ is low (low $E$), the exponential factor goes to zero and $M = 1$. In order to produce multiplication, large values of $\alpha(x)$ (large $E$) are required so that $M$ increases rapidly, eventually exponentially. Briefly, the amplification regions can be summarized as follows:

- Ionization region: $M = 1$
- Proportional region: $1 < M = \text{constant}$
- Avalanche region: $1 \ll M < \infty$

In the ionization chamber region the charge $Q$ produced by the incident particle is measured directly, i.e.

$$Q = E/IE$$

(Eq. 6.2)
Where $E$ is the kinetic energy of the particle and $I$ is the ionization energy of the gas; $Q$ is the resulting charge measured in the ionization chamber. Ionization chambers are utilized in situations where it is desired to measure the energy of the particle accurately. They also find application in smoke detectors, radon detectors and radiation therapy. Illustrations are shown in Figs. 6.3 and 6.4.

Fig. 6.3 Schematic of a simple ionization chamber that measures the pulse in terms of a current. If the ammeter is replaced by a capacitor, individual pulses can be measured.

Fig. 6.4 Ionization chamber schematic (left) and a measure of the ion diffusion velocity for various commonly employed gases as a function of the diffusion distance $x$ and the pressure $P$. 
In the **proportional counter** mode, charge is measured both directly and indirectly. The higher voltage \( U_0 \) produces a larger signal but because of the amplification the signal is only proportional to the particle energy.

\[
Q \propto E / IE
\]  
(Eq. 6.3)

Proportional counters are useful for measuring charged particles, as well as weakly ionizing particles such as electrons or very energetic protons, where the signal requires significantly more amplification to be detected. While the signal is proportional to energy (\( M \sim \text{constant} \)), particle energy determination is less straightforward.

**Avalanche counters** amplify the direct charge exponentially (Townsend avalanche)

\[
Q \propto \int dx \left( \frac{dE}{dx} \right) f(x).
\]  
(Eq. 6.4)

They are most useful for detection of minimum-ionizing particles in which detection of the particle is more important than its energy. Similarly, the **Geiger counter** registers events, but provides no particle energy information, other than the particle has created sufficient ionization to exceed the electronic detection threshold (\( Q = \text{const} \neq f(E) \)). A schematic diagram of a Geiger counter is shown in Fig.6.5.

![Fig 6.5 Schematic concept of a Geiger counter. A positive voltage \( U_0 \) is applied to a wire of radius \( R_1 \) inside a gas-filled tube at ground potential with a of radius \( R_2 \).](image)

The effects of gas pressure and applied voltage are shown in Fig.6.6 for a detector filled with methane gas. Consistent with Eq. 6.1, this figure demonstrates that high multiplication factors are favored by low pressures and high applied voltages.
Semiconductor detectors

Two major limitations of gas detectors are (1) the low density of the stopping medium, thereby making it difficult to stop energetic particles, and (2) the drift time of the electrons to the anode, which decreases energy and timing resolution. Solid state detectors that utilize semiconductor materials overcome this problem because of the much greater density they provide and rapid collection times. In a sense, semiconductor detectors work on the same principle as gas ionization counters, except that the electrodes are formed by a p-n junction instead of two separated electrodes of opposite polarity. An additional advantage of semiconductors is the low energy required to create an electron pair: 3.6 eV for silicon and 3.0 eV for germanium.

The detectors operate as follows. Starting with a group IVA element (e.g. Si or Ge), an impurity is introduced into the lattice. If the impurity is a group VA element (e.g. As or P),...
P), then we have an “excess” electron in the lattice, or **n-type material**, as shown in Fig. 6.7.

![n-type diagram](image)

Fig. 6.7 Lattice structure for n-type semiconductors in which a phosphorus impurity atom is inserted into the lattice.

If the impurity is a Group IIIA element (e.g. B or Al), then we have a “deficiency” of an electron or **p-type material**, as shown in fig.6.8.

![p-type diagram](image)

Fig 6.8 lattice structure for p-type semiconductors in which a boron impurity atom is inserted into the lattice.

When an electric field is placed across n-type or p-type material, we observe electron and hole migration. For example, in Fig. 6.9 the extra electron in phosphorus will migrate toward the positive potential, leaving a cation (hole), which then migrates to the negative potential.
Fig. 6.9 Top: A potential is applied across n-type silicon, causing the extra electron in phosphorous to migrate toward the positive potential. Middle: A silicon electron then migrates to the negative potential to fill the vacancy in phosphorous, leaving a hole in the lattice. Bottom: net effect is the migration of holes to the negative potential and electrons toward the positive potential.

If a sandwich of n-type and p-type material is made, “excess” electrons from the n-type material at the interface migrate/diffuse over to the extra vacancies in the p-type creating a **depletion zone**. Inside this depletion zone there are no excess charge carriers. Before diffusion, both n-type and p-type sides of the junction were electrically neutral. The diffusion however makes the n-type slightly positive and the p-type side slightly negative. For Si this difference is 0.6 volts. The device we have just constructed is called a **diode**. The difference in potential between the n and p sides is called the **junction potential**. It stops further diffusion. A hole (+) does not want to go where it is already positive, so it is repelled. Therefore, no current flows through the diode. The p-n junction is illustrated in Fig. 6.10.
Fig. 6.10 Top to bottom: steps in creation of a depletion layer and potential difference in a p-n junction.

Suppose we hook the diode up to a battery, as illustrated in Fig. 6.11. If we apply forward bias (voltage), the voltage on the battery reduces or overcomes the barrier presented by the junction potential. However, if reverse bias is applied, the size of the barrier will increase, thus restricting current flow.

How can we get current to flow through the diode? For this to happen, the charge carrier (electron or hole) must have enough kinetic energy to overcome the barrier (potential difference). This can be caused either by thermal energy or by the passage of radiation through the p-n junction.
Fig 6.11 (a) p-n junction with no bias applied; (b) reverse bias in which positive bias is applied to the n-type material, increasing the junction barrier, and (c) forward bias in which positive bias is applied to the p-type material, reducing the barrier.

When operated in the reverse-bias configuration, silicon semiconductor detectors are particularly effective for the measurement of highly ionizing radiation. The electron-hole pairs created in the depletion region are rapidly collected with high efficiency, making them especially useful for measuring particle energies and giving them excellent timing properties. Another advantage is that they can be segmented into multiple components that permit highly sophisticated detector arrays. The limitation of silicon is that it is difficult to obtain depletion layers greater than 5 mm. Much thicker semiconductor devices for study of energetic particles or gamma rays can be constructed from high-purity or lithium-drifted germanium. However, these must be operated at low temperatures to prevent thermal leakage across the junction.

- **Scintillation Detectors**

The basic principle of scintillator operation is the creation of electronic excitations that produce visible or near visible light in the scintillating medium when exposed to radiation. Rutherford’s scattering experiment that established the structure of the atom used ZnS crystals to produce the scintillations, which were recorded with the naked eye. In modern detectors the scintillation light is collected on a photocathode that converts the light into electrons. The electrons are then amplified in a photomultiplier tube to produce...
an electronic signal. The amount of light emitted is proportional to the energy deposited in the scintillator. An alternative method is to attach a photodiode directly to the crystal to obtain an electronic output.

A schematic diagram of a scintillator detector is shown in Fig. 6.12.

Fig. 6.12  Schematic diagram of a scintillation detector. From top to bottom, incident radiation enters the scintillator and creates light. The scintillator is surrounded by a highly reflective material that prevents light loss. The light is then collected on a photocathode inside an evacuated photomultiplier tube. The electrons emitted from the photocathode are focused on to a series of dynodes that amplify the signal to produce an electronic output.

Several materials serve as effective scintillators. For solid-state applications used in the measurement of gamma rays and energetic nuclear particles, sodium iodide doped with thallium NaI(Tl), cesium iodide doped with thallium CsI(Tl), or plastics are frequently employed. Liquid scintillators based on polyaromatic hydrocarbon structures such as anthracene, phenanthrene and stilbene are widely used in biochemistry for detection of tritium- and $^{14}$C-labelled compounds. Liquid scintillator loaded with gadolinium, which
has a very large probability for $n, \gamma$ reactions is an important method of detecting neutrons.

**Solid State vs. Scintillator Detectors**

Thallium doped sodium iodide [$\text{NaI(Tl)}$] scintillation detectors are used for detection of gamma rays in the energy range $E_\gamma = 0.1 - 100$ MeV, when high efficiency ($\epsilon = 10 - 60\%$) and moderate energy resolution ($\Delta E_\gamma / E_\gamma = 5 - 15\%$) are required. The detection efficiency of NaI(Tl) detectors generally improves with increasing crystal volume, whereas the energy resolution is largely dependent on the crystal growth conditions. Lithium-drifted germanium [$\text{Ge(Li)}$] detectors are typically used to detect photons at lower energies with lower efficiencies, but with a gamma ray energy resolution of $\Delta E_\gamma / E_\gamma = 0.1 - 1\%$. The higher energy resolution is essential in radioactive counting situations where a large number of lines are present in a gamma ray spectrum. It should be mentioned that a Ge(Li) detector is far more expensive to purchase and to maintain than a NaI(Tl) detector. This is because the Ge(Li) detector crystal must be kept at liquid nitrogen temperature (77 K) at all times to maintain the density profile of the lithium drifting in the Ge crystal.

Many radionuclides can be identified by examining the characteristic gamma rays emitted in the decay of the radioactive "parent" to a "daughter" nucleus. In fig. 6.13 the decay of $^{22}\text{Na}$ measured with a NaI detector (scintillator) is compared with that of a Ge detector (solid state).

**Fig. 6.13** Spectrum of $^{22}\text{Na}$ gamma rays measured in a NaI(Tl) detector (top) and in a Ge(Li) detector (bottom).

$^{22}\text{Na}$ decay occurs by one of two independent mechanisms:

1. Positron decay to one of two final states, the ground state of $^{22}\text{Ne}$ and an excited state at 1.275 MeV.
$^{22}\text{Na} \rightarrow ^{22}\text{Ne}(\text{g.s.}) + \beta^+ + \nu(0.06\% \text{ of all decays}), \text{ and}$

$^{22}\text{Na} \rightarrow ^{22}\text{Ne}^*(1.275 \text{ MeV}) + e^+ + \nu(90.4\% \text{ of all decays})$.

In both cases a positron and a neutrino are emitted, and the net nuclear charge changes from $Z = 11$ to $Z = 10$. The $^{22}\text{Ne}$ ground state (g.s.) is stable; however, the first excited state of $^{22}\text{Ne}$ at 1.275 MeV decays with a lifetime of 3.7 ps in the gamma decay process.

$^{22}\text{Ne}^*(1.275 \text{ MeV}) \rightarrow ^{22}\text{Ne}_{\text{g.s.}} + \gamma_{1.275}$.

This mode gives rise to a characteristic gamma ray with energy 1.275 MeV. The positrons slow rapidly in the radioactive source material and disappear in the annihilation process

$$e^+ + e^- \rightarrow 2 \gamma_{0.511 \text{ MeV}},$$

producing two characteristic 0.511 MeV annihilation gamma rays.

(2) Electron Capture. In this decay process, an atomic electron is captured by the $^{22}\text{Na}$ nucleus in the reaction

$$^{22}\text{Na} + e^- \rightarrow ^{22}\text{Ne}^*(1.275 \text{ MeV}) + \nu(9.5\% \text{ of all decays})$$

and a monoenergetic neutrino is emitted. The electron capture process populates only the first excited state of $^{22}\text{Ne}$ at 1.275 MeV and therefore characteristic 1.275 MeV gamma rays result. Annihilation gamma rays at 0.511 MeV are not produced in electron capture because positrons are not created.

In Fig. 6.13 two peaks and two broader structures are observed in each spectrum. Clearly the Ge(Li) detector has the best resolution. The explanation of the spectrum is as follows. The peak at 1.275 MeV corresponds to events in which the entire energy of the gamma ray is collected in the detector via the photoelectric effect. $^{22}\text{Na}$ decays via positron emission. Therefore positron annihilation is also observed in the detector at 0.511 MeV. In addition to the peaks at 0.511 and 1.275 MeV, two Compton "edge" structures labeled CE1 and CE2 are seen in the spectra of both detectors. CE2 corresponds to an event in which a single gamma ray: (a) enters a detector with 1.275 MeV, (b) reverses its direction completely in a Compton backscattering collision with an electron in the detector, and (c) exits the detector volume without further loss of energy. The energy lost by the backscattered gamma ray is transferred to the recoiling electron which slows in the detector, producing the observed signal. An analogous Compton process occurs for 0.511 MeV gamma rays, resulting in the Compton edge CE1. The 0.511 MeV gamma ray peak actually sits on the Compton "plateau" generated by 1.275 MeV gamma rays.
- **Neutron Detection**

Since neutrons are neutral particles and do not undergo electromagnetic interactions, as is the case with photons, their stopping mechanism is primarily via collisions with other nuclei. The possible outcomes of such collisions as a function of neutron energy $E_n$ can be summarized as follows:

- $E_n > 10$ MeV: nuclear reactions; reaction products ionize the detector medium.
- $E_n < 10$ MeV: elastic neutron-nucleus scattering.
- $E_n \approx 1/40$ eV: thermal diffusion; little energy loss or absorption.

One method of detecting neutrons is use organic scintillators (liquid or solid), which scatter neutrons primarily off the hydrogen and carbon nuclei in the compound. Momentum conservation tells us that the maximum recoil energy is obtained when the neutron is scattered off one of the H atoms. The recoiling charged proton generates a signal in the scintillator that can be amplified in the same manner as in charged-particle detection. Because the scattering process does not lend itself to complete charge collection, even in very thick detectors, measurement of neutron energies usually depends on time-of-flight (TOF) techniques, since

\[
E = \frac{1}{2} mv^2 = \frac{1}{2} m \frac{s^2}{t^2}
\]

Since we know $m$ (mass of the neutron), and can measure the distance of the time-of-flight $s$, by measuring $t$ we can determine $E$. For this purpose one wants to use a “fast scintillator”, that is, one that has a < 2ns response to the incident radiation.

A second common method of detecting neutrons involves the use neutron-capture reactions on nuclei with very high cross sections such as $^{10}$B. By using $^{10}$BF$_3$ gas in an ion chamber, neutrons can be detected from the reaction products of the neutron-capture reaction

\[
^1n + ^{10}B \rightarrow ^7Li + ^4He.
\]

The ion-chamber detects the charged particles, thus identifying the presence of the neutron.

From the point of view of Nuclear Safeguards and Homeland Security, the detection of neutrons is of vital importance. Large quantities of fissionable material emit neutrons that are not easily shielded because of their neutral nature. Neutron detectors are used extensively to monitor land, sea and air cargo entering the United States, as well as many other countries. An outline of one such approach to mobile neutron detection is shown in Fig.6.14 (taken from [http://www.ortec-online.com/papers/cartop_inmm04.pdf](http://www.ortec-online.com/papers/cartop_inmm04.pdf))
Car drives around at 10, 20, or 30 mph and monitors levels of gamma and neutron radiation.

Equipment
The NaI-SS system used in these measurements consists of a 4” x 4” x 16” sodium iodide (NaI) detector, 4 each 1” x 18” $^3$He tubes at 20 atm in a high density polyethylene moderator, both connected to a digiBASE, a GPS, and a laptop with special software, built into a standard roof-mounted car carrier. The entire system is powered from the 12 VDC car outlet. Figure 1 shows the system mounted on a car.

Fig. 6.14 Mobile neutron detection system for Homeland Security.