I. Charged Particle Detectors

A. Scintillators
B. Gas Detectors
   1. Ionization Chambers
   2. Proportional Counters
   3. Avalanche detectors
   4. Geiger-Muller counters
   5. Spark detectors

C. Solid State Detectors

II. Gamma ray detection (Scintillators, Solid State dets.)

III. Neutron detection
Gas detectors

Energy required to form and ion-pair (IP)
Gases: 20-30 eV/IP
Si: 3.6 eV/IP
Ge: 3.0 eV/IP
**Ionization chamber**: Measures charge directly produced by the incident particle.

\[ Q = \frac{E}{IE} \]

where \( E \) is the energy of the particle and \( IE \) is the ionization energy of the gas; \( Q \) is the resulting charge measured in the ionization chamber.

**Proportional counter**: Measures charge both directly and indirectly created.

\[ Q \propto \frac{E}{IE} \]

**Avalanche counter**: Amplifies direct charge exponentially (Townsend avalanche)

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

**Geiger counter**: 

\[ Q = \text{const} \neq f(E) \]

Ionization Chamber (radon detectors, smoke detectors, radiation therapy)

Instead of an ammeter, we can use a capacitor and measure the individual ionizing events (e.g. each alpha particle).

![Diagram of an ionization chamber and Geiger counter](image)
Frisch gridded ionization chamber

Drift velocity in different gases
Proportional and Avalanche Counters

Gas Amplification:

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

Ionization region : M=1
Proportional region: 1 < M = constant
Avalanche region: 1 << M < infinity

\[ \frac{\alpha}{P} = f\left(\frac{E}{P}\right) \]

E=Electric field = V/d
P=Pressure

\[ \frac{E}{P} = \text{reduced electric field. You want } \frac{E}{P} \text{ large in order to produce multiplication.} \]
Classic coaxial design of a proportional counter

\[
\begin{align*}
E(\tau) &= \frac{U_0}{\ln \left( \frac{R_2}{R_1} \right)} \left( \frac{1}{\tau} \right) \\
&+ \text{Ionization}
\end{align*}
\]
How should we read the curves for a proportional counter below?
Solid State detectors:

Starting with type IVA material (e.g. Si or Ge), let’s introduce some impurities into the lattice.

If impurity is P, As (Type VA) then we gave an “excess” electron forming an “n type material”

If impurity is B, Al (type IIIA) then we have a “deficiency” of an electron (called a “hole”) thus forming a “p type material”
When an electric field is placed across n-type or p-type material, we observe electron and hole motion.

*FIGURE 5.5* Directions of hole and electron movement in a crystal.
Now let’s build a sandwich of n-type and p-type material. At the interface, “excess” electrons from the n-type migrate/diffuse over to the extra vacancies on 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 side 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. Consider a hole (+) does not want to go where it is already positive, it is repelled. Therefore, no current flows through the diode.
Suppose we hook the diode up to a battery. Forward bias → the voltage on the battery reduces or overcomes the junction potential. Reverse bias → the orientation of the battery increase the size of the barrier.

How can we get current to flow through the diode? the charge carrier (electron or hole) must have enough kinetic energy to overcome the barrier (potential difference).

thermal energy
energy from radiation
Gamma ray detection:

Scintillators:
Basic Mechanism – Incident $\gamma$ radiation produces $\beta^+$ and $\beta^-$. These beta particles (electrons and positrons) deposit their kinetic energy in the crystal exciting it. The decay of the excited crystal produces light in the visible or near visible region of the electromagnetic spectrum.

Scintillator materials: NaI, NaI(Tl), CsI(Tl)
Solid State vs. Scintillator

- Thallium doped, sodium iodide [NaI(T)] scintillation detectors are used for detection of gamma rays in the energy range $E = 0.1 - 100$ MeV, when high efficiency (10 - 60%) and moderate energy resolution ($E/E = 5 - 15\%$) are required.
- The detection efficiency of NaI(T) detectors generally improves with increasing crystal volume, whereas the energy resolution is largely dependent on the crystal growth conditions.
- Lithium-drifted germanium [Ge(Li)] detectors are typically used to detect photons at lower energies with lower efficiencies, but with a gamma ray energy resolution of $E/E = 0.1 - 1\%$. 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(T) 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.
Let’s examine the decay of $^{22}$Na with a NaI detector (scintillator) and a Ge detector (solid state).

- Which spectrum has better resolution? Why?

- What are the sharp peaks in the spectrum?

- What is the remaining structure, particularly the features labeled CE1 and CE2 (CE stands for Compton edge)?
Explanation:
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. A count at 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.
The $^{22}$Na decay occurs by one of two independent mechanisms.

1. **β+ Decay:** In each of the two beta decay branches

   \[ ^{22}\text{Na} \rightarrow ^{22}\text{Ne}(\text{g.s.}) + e^+ + \nu (0.06\% \text{ of all decays}) \]

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

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

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

   which 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

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

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.
Neutron Detection:

E_n > 10 MeV: nuclear reactions; reaction products may ionize
E_n < 10 MeV: elastic neutron-nucleus scattering
E_n ≈ 1/40 eV: thermal diffusion; little energy loss or absorption.

How can we distinguish neutrons from gamma rays?
• If the neutrons are slow we can do it by time-of-flight since gammas travel at the speed of light
• If the neutrons are fast, we can distinguish them via pulse shape discrimination (PSD).

The data of the $^{18}$O+$^{12}$C→$^{17}$O+$^{13}$C reaction at 84 MeV are plotted.
The two dimensional spectrum showing neutron-gamma separation can be linearized to yield the following resolution as a function of energy.
Scintillators (liquid or solid): Scatter neutrons off an organic scintillator (lots of H). The recoiling proton generates a signal in the scintillator. Amplify the scintillation with a photomultiplier tube (PMT).

Can also determine the neutron energy by measuring the time-of-flight (TOF).

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

If we know \( m \) (that it is a neutron), and we know the distance \( s \) over which we measure the time-of-flight, then by measuring \( t \) we can determine \( E \).

For this one wants to use a “fast scintillator” that is one that has a < 2ns response to the incident radiation.

Capture: \(^{10}\text{BF}_3\) gas in an ion chamber.

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

The resulting charged particles are moving and so are easy to detect. An example of this would be an ionization chamber in which the gas utilized would be \(^{10}\text{BF}_3\).
Homeland Security – Monitoring transport of illicit materials

**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” ³He 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.

Car drives around at 10, 20, or 30 mph and monitors levels of gamma and neutron radiation.

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