Detectors of Radiation

Marcel Miglierini
Department of Nuclear Physics and Technology
Slovak University of Technology
Bratislava, Slovakia

TABLE OF CONTENTS

I. Radiation

Four types of radiation are discussed:
- Alpha (α) – $E_{max} \approx 20$ MeV
- Beta (β) – $E_{max} \approx 10$ MeV
- Gamma (γ) – $E_{max} \approx 20$ MeV
- Neutron (n) – $E_{max} \approx 15$ MeV

This radiation with the quoted maximum energies is encountered around nuclear reactors, around installations involving production or use of natural or manufactured radionuclides, and also around low energy accelerators.

Alpha particles:
- The alpha particle is a helium nucleus (2 protons, 2 neutrons) produced from the radioactive decay of heavy metals and some nuclear reactions.
- The high positive charge (2+) of an alpha particle causes electrical excitation and ionization of surrounding atoms.
- Alpha particles are the least penetrating radiation featuring a relatively straight path over a short distance (several cm in air).
- The specific ionization of alpha particles is very high.

Beta particles:
- There are two types of beta particles: electron (β^-) and positron (β^+). These are ejected from the nucleus of a beta-unstable radioactive atom ("neutron-rich" and "neutron-deficient" or "proton-rich" nucleus, respectively).
- The beta has a single negative or positive electrical charge and very small mass.
- The interaction of a beta particle and an orbital electron leads to electrical excitation and ionization of the orbital electron.
- Beta particles follow a tortuous path (zig-zag).
- The specific ionization of a beta particle is low due to its small mass, small charge, and relatively high speed of travel.
- The interaction of β^+ (positron) with an electron leads to their annihilation and occurrence of two annihilation photons with the energy of 0.511 MeV.

Gamma rays:
- The gamma ray is a photon of electromagnetic radiation with a very short wavelength and high energy.
- Gamma rays are emitted from unstable atomic nuclei and have high penetration power.
- The specific ionization of gamma is low compared to that of an alpha particle, but is higher than that of a beta particle.

Neutrons:
- Neutrons have no electrical charge and have nearly the same mass as a proton.
- Neutrons are fairly difficult to stop, and have a relatively high penetrating power.

II. Principles of Detection

Detection of radiation is based on its interactions and the energy deposited in the material of which the detector is made. The ultimate goal is a formation of electron-ion pair inside the working volume of the detector because at the final stage of detection only electrically charged particles can be registered. They are collected on electrodes with the opposite charge due to voltage applied between them (Fig. 1).
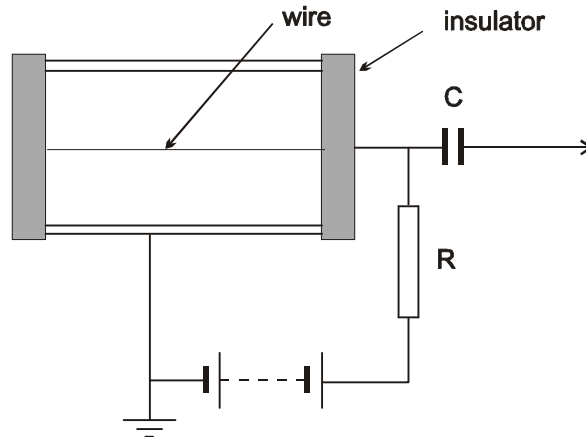

Figure 1 Schematic diagram of detection of radiation.

The collection of electric charges created by electron-ion pairs reduces the voltage across the capacitor (C), causing a pulse across the resistor (R) that is recorded by an electronic circuit. The height of the pulse is given by:

$$\Delta V = \frac{A.n.e}{C} \tag{1}$$

where ΔV is pulse height, C is the detector capacitance, n denotes initially formed electron-ion pairs, e is charge of electron (1.602×10^{-19} C), and A refers to an amplification factor, *i.e.* electron-ion pair production caused by secondary ionization.

Because a presence of electrically charged particles (electrons and/or ions) in the active volume of a detector is crucial, from the point of view of interaction mechanisms we divide the radiation into three groups:

- charged particles: electrons, positrons, protons, deuterons, alphas, and heavy ions (A > 4)
- photons: gamma and X-rays
- neutrons

Charged particles

1. Coulomb interactions: - in practice only interactions with electrons are considered (R^2 atom/R^2 nucleus $\approx 10^8$)
   – electrical forces extend over long distances => no direct contact of the particles is needed
   i. inelastic collisions:

      a) excitation (Fig. 2) – X-ray after 10^{-8} to 10^{-10} s
      b) ionization (Fig. 3) – fast electrons produced are called δ rays
           – electron-ion pair is formed
    ii. elastic collisions (Fig. 4) – not important for detection
2. bremsstrahlung (Fig. 5) – emission of electromagnetic radiation due to acceleration/deceleration of free charged particle
   – important only for light particles (electrons) in high-Z materials
3. nuclear interactions – can be neglected for the energies considered
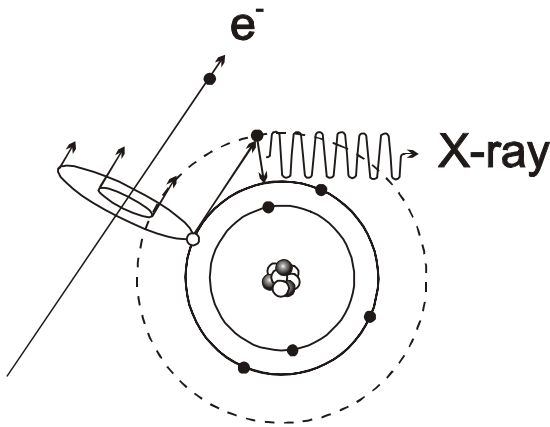4. Cerenkov radiation – used only in Cerenkov counters

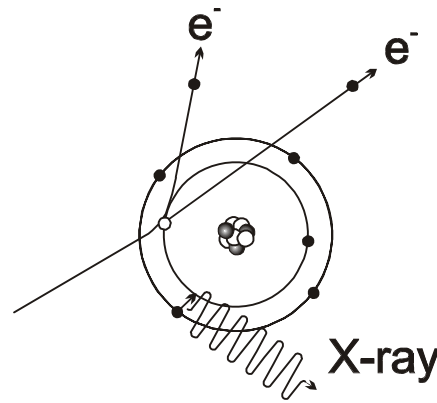Figure 2 Inelastic collision: excitation.
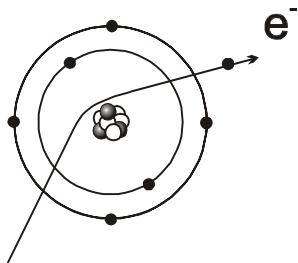

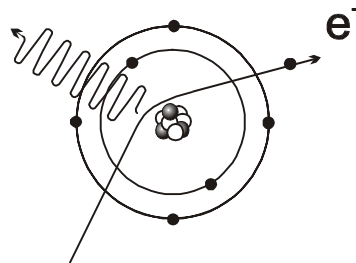Figure 3 Inelastic collision: ionization.

Figure 4 Elastic collision.

Figure 5 Bremsstrahlung.

Photons

Can be considered as particles with no charge and zero rest mass which travel with the velocity of light:

1. Photoelectric effect (Fig. 6) – interaction with an orbital electron
   – electron-ion pair is formed, expulsion of high energy electron
2. Compton scattering (Fig. 7) – an elastic collision of photon and electron occurs
   – ionization with high energy beta and gamma
3. Pair production (Fig. 8) – for $E_\gamma > 1.02$ MeV passing close to a heavy nucleus
   – electron – ionization
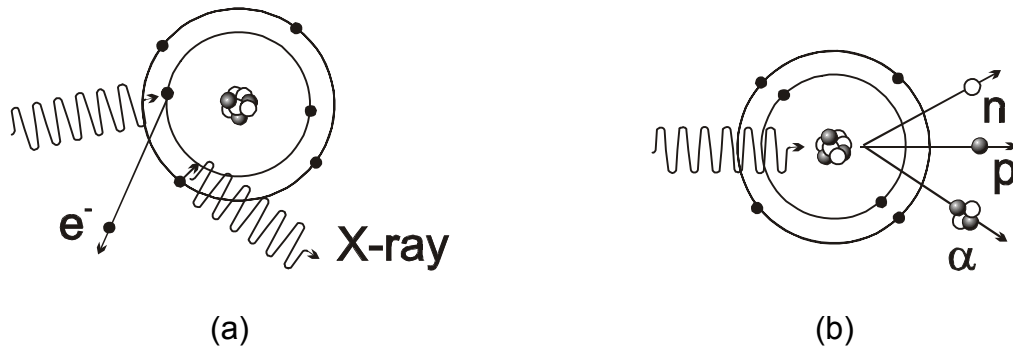   – positron – ionization and annihilation

(a)   (b)

Figure 6 Photoelectric effect (a) and nuclear photoelectric effect (b).
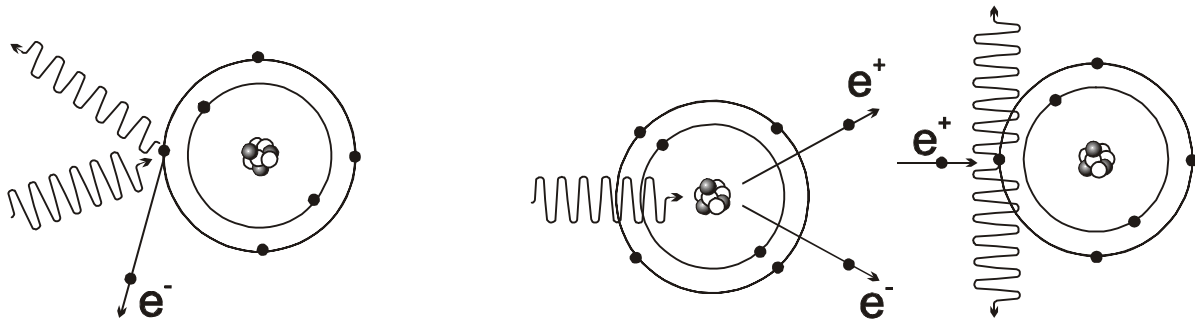

Figure 7 Compton scattering.   *Figure 8* Pair production with subsequent annihilation.

Neutrons

Interact with nuclei only through nuclear forces:

1. scattering: $n + {}_Z^A X \rightarrow {}_Z^A X + n$
    i. inelastic scattering (Fig. 9) – excitation of a nucleus with subsequent emission of a gamma photon and neutron
        – compound nucleus mode
    ii. elastic scattering (Fig. 10) – occur between fast neutrons and low atomic mass number absorbers ("billiard ball effect")
        – no excitation occurs
2. absorption:
    i. radiative capture (Fig. 11):
        a) (n, 2n) reaction: $n + {}_Z^A X \rightarrow {}^{A-1} X + 2n$

        b) (n, p) reaction: $n + {}_Z^A X \rightarrow {}_{Z-1}^A Y + p$

        c) (n, α) reaction: $n + {}_Z^A X \rightarrow {}_{Z-2}^{A-3} Y + {}_2^4 \alpha$

        d) (n, γ) reaction: $n + {}_Z^A X \rightarrow {}_Z^{A+1} X + \gamma$

    ii. fission (Fig. 12): $n + {}_Z^A X \rightarrow {}_{Z_1}^{A_1} Y_1 + {}_{Z_2}^{A_2} Y_2 + n + n + \ldots$

        – caused by either fast or thermal neutrons
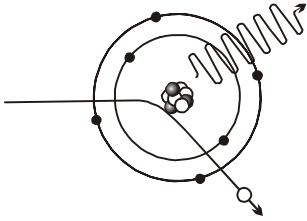   – dissipation of energy causes ionization
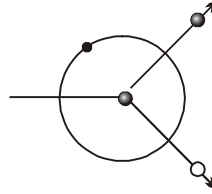
Figure 9 Inelastic scattering of neutrons.

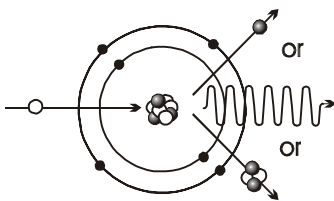*Figure 10* Elastic scattering of neutrons.

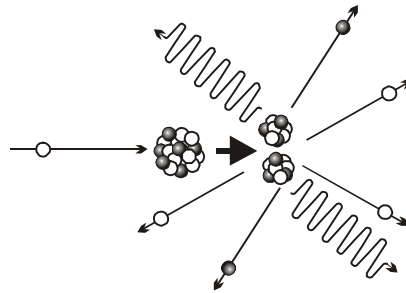*Figure 11* Radiative capture of neutrons.

Figure 12 Fission by neutrons.

III. Gas-Filled Detectors

Gas-filled detectors operate by utilising the ionization produced by radiation as it passes through a gas. Typically such a counter consists of two electrodes to which a certain electrical potential is applied. The space between the electrodes is filled with a gas (Fig. 13). Ionizing radiation, passing through the space between the electrodes, dissipates part of its energy by generating electron-ion pairs. Both electrons and ions are charge carriers that move under the influence of the electric field. Their motion induces a current on the electrodes, which may be measured. Or, through appropriate electronics, the charge produced by the radiation may be transformed into a pulse, in which case particles are counted individually. The first type of counter is called *current* or *integrating chamber*; the second type is called *pulse chamber*.
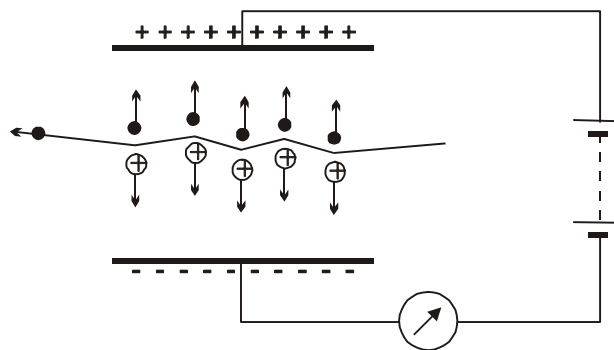

Figure 13 Principle of a gas-filled detector.

To achieve the high field intensity needed for gas multiplication without excessive applied voltage, chambers are usually cylindrical in shape with a very thin wire stretched axially at the centre of the counter (Fig. 1).

Up to now we have mentioned the effects of ionization produced directly by the incident particle. This is called *primary ionization*. There are types of gas counters in which the electric field is so strong that the electrons of the primary ionization acquire enough kinetic energy between collisions to produce new electron-ion pairs. These new charges constitute the *secondary ionization* giving rise to an electron avalanche (Fig. 14.). This multiplication of electrons is called gas amplification or Townsend avalanche. Primary and secondary ionization are generated within such a short period of time that they contribute to one and the same pulse.
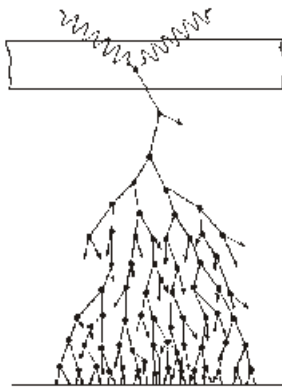

Figure 14 Secondary ionization (Townsend avalanche).

Gas counters take their name from the voltage region ion which they operate. The relationship between voltage applied to the counter and charge collected is shown in Fig. 15. The curve for alpha particles is higher than the beta curve in Region I to part of Region IV due to larger number of electron-ion pairs produced by the initial reaction of the incident radiation. Distinctions in the type of incident radiation are negated once the detector voltage is sufficiently increased (beyond Region IV). Since then the detector discharges with each initiating event.
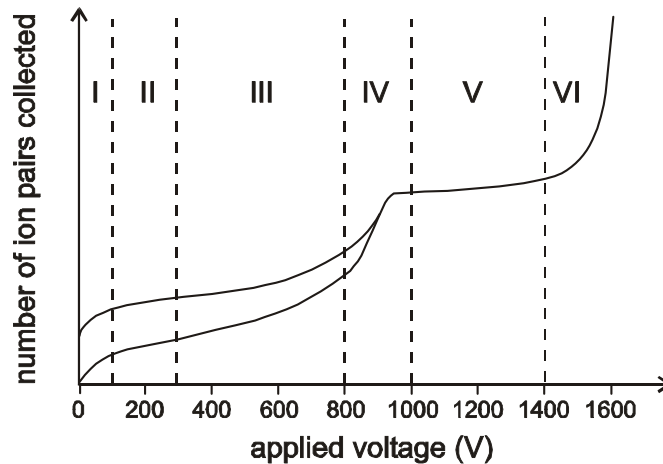

Figure 15 The relationship between the voltage applied to a gas-filled counter and charge collected.

Gas amplification regions

Gas amplification regions are illustrated in Fig. 15:

I. Recombination region
    - voltage so low that recombination takes place before any charge is collected at the electrodes
    - no counters operate in this region

II. Ionization region
    - voltage sufficient to ensure that all electron-ion pairs produced by the incident radiation are collected
    - no gas amplification takes place

III. Proportional region
    - all electron-ion pairs are collected
    - gas amplification ($A \sim 10^3 - 10^4$) is proportional to the applied voltage

IV. Limited proportional region
    - additional processes occur leading to increased ionization
    - positive ions remain near their point of origin, further avalanches are impossible
    - no counters operate in this region

V. Geiger-Müller region
    - electron-ion pair production is independent on the type of incident radiation
    - electric field strength so high that the discharge continues to spread until amplification cannot occur, due to a dens positive ion sheath surrounding the anode

VI. Continuous discharge region
    - the applied voltage is so high that, once ionization takes place, there is a continuous discharge

Ionization chambers

- output signal proportional to the particle energy => identification of the type of particle and its energy
- signal is not large => only strongly ionizing particles (α, p, fission fragments, heavy ions) are detected
- energy range > 10 keV
- pulse counting ionization chamber and integrating ionization chamber
- parallel plate (Fig. 13) or concentric cylinder design (Fig. 1), gas: air
- "window" for α and/or β
- detection of neutrons (see below)
- gamma sensitivity is reduced by decreasing the amount of chamber gas or increasing the boron coated surface area

Proportional counters

- identification of the any type of particle (α, β, γ) and its energy
- gas: helium, argon, (α, β, γ) or boron triflouride (neutrons)
- free electrons are produced by secondary ionization, photoelectric interactions, and bombardment of the cathode surface by positive ions
- detection of low energy particles (< 10 keV) is possible due to internal amplification
- quenching gas (methan) => limited lifetime => gas flow counters

Geiger-Müller counters

- Geiger-Müller region
  - number of electrons produced is independent of applied voltage
  - number of electrons produces is independent of the number of electrons produced by the initial radiation
- identification of the type of radiation (number of original ion pairs) is impossible
- information only about the number of particles
- positive ion sheath around the central wire => reduced field strength -> quenching gas
- finite lifetime due to degradation of the filled-in gas
- use limited to low counting rates due to large dead time
- sensitive detectors -> portable instrumentation, simple counting circuit, ability to detect low-level radiation

IV. Detection of Neutrons

Since neutrons do not directly ionize atoms, they are detected "indirectly" upon producing a charged particle or a photon, which is then recorded with the help of an appropriate detector. The charged particle or the photon is the result of a neutron interaction with a nucleus. If the mechanism of the interaction is known, information about the neutron can be extracted by studying the products of the reaction. Many types of interactions are used, divided into *absorptive* and *scattering* reactions (see Section II).

BF$_3$ Counter

The (n, α) reaction with ^{10}B is probably the most useful reaction for the detection of thermal neutrons. ^{10}B is a constituent of the compound BF$_3$, which may be used as the gas of a proportional counter or ionization chamber. The BF$_3$ counter detects the alphas and the lithium particles produced by the reaction:

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li^{+++} + ^{4}_{2}He^{++} + 5e^{-}$$
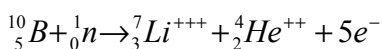
Boron-lined counters

Boron-lined counters are gas-filled proportional counters that employ the same reaction as the BF_3 counter, except that the ^{10}B is coated on the walls of the counter (Fig. 16).
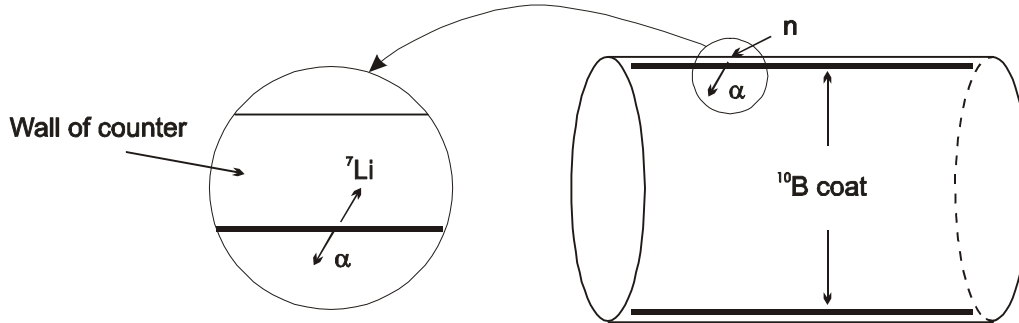

Figure 16 Boron-lined counter.

Fission chambers

Fission chambers are gas counters that detect the fragments produced by fission. In the most common type of fission counter, the interior surface of the detector is coated with a fissile isotope (Fig. 17). When fission takes place, one of the fission fragments (denoted as FF_1 in Fig. 17) is emitted towards the centre of the counter and is detected. The other (FF_2) stops in the fissile deposit or the wall of the counter. The counting rate of a fission counter is proportional to the fission rate, which in turn is proportional to the neutron flux. Fission counters may be used for detection of either fast or thermal neutrons.
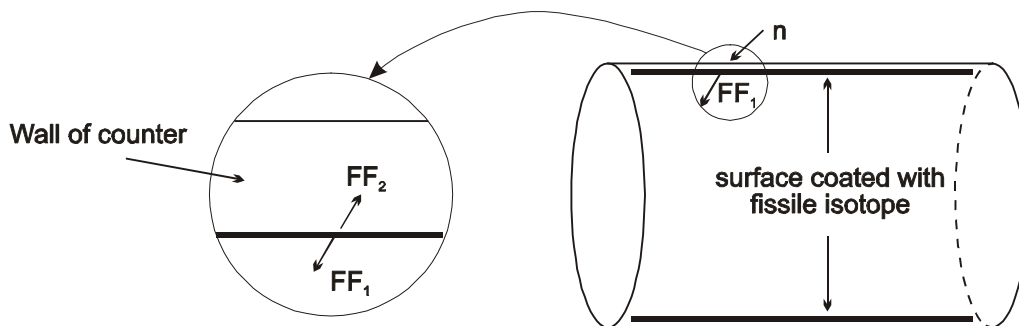

Figure 17 Fission counter.

Compensated ionization chamber

Compensated ionization chamber consists of two separate chambers; one chamber is coated with boron, and one chamber is not. The coated chamber is sensitive to both gamma rays and neutrons, while the uncoated chamber is sensitive only to gamma rays. Subtraction of currents from both chambers is done electrically so that the net output of both detectors is read and the signal is proportional to the neutrons detected (Fig. 18).
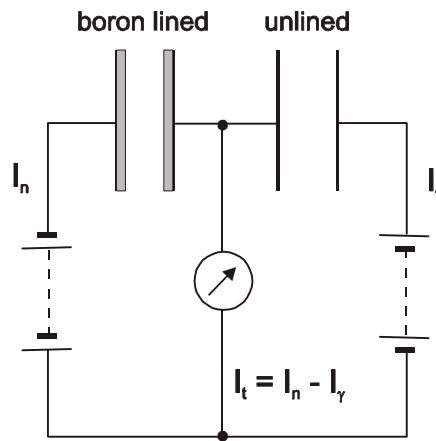
Figure 18 Compensated ionization chamber.

The boron coated chamber is referred to as the working chamber; the uncoated chamber is called the compensating chamber.

V. Scintillation Detectors

Principles of Operation

Scintillators are materials - solids, liquids, gasses - that produce sparks or *scintillation* of light when ionizing radiation passes through them. The first solid material used as a particle detector was a scintillator. The operation of a scintillation counter may be divided into two steps:
1. Absorption of incident radiation energy by the scintillator: electrons are raised to excited states and after subsequent de-excitation the scintillator emits a photon in the visible light range.
2. The photon, emitted from the scintillator, interacts with the photocathode of a photomultiplier tube (Fig. 19), releasing electrons. The electrons emitted by the photocathode are guided, with the help of an electric field, towards the first dynode, which is coated with a substance that emits secondary electrons, if electrons impinge upon it. The secondary electrons from the first dynode move towards the second, from there towards the third, and so on. Typical commercial phototubes may have up to 15 dynodes. The production of secondary electrons by the successive dynodes results in a final amplification (10^6 or higher). The voltage difference between two successive dynodes is of the order of 80-120 V.
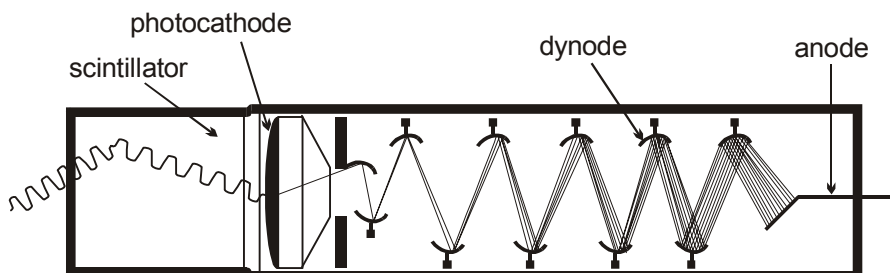

Figure 19 Photomultiplier tube.

Types of Scintillators

The different types of scintillators include:

Inorganic crystals
- alkali iodides that contain a small concentration of an impurity, e.g. NaI(Tl), CsI(Tl), CaI(Na), LiI(Eu), and CaF_2(Eu) or ZnS
- high efficiency for detection of gamma rays
- pulse decay time of about 1 microsecond

Organic scintillators
- aromatic compounds: naphthalene, stilbene, anthracene
- pulse decay time of about 10 nanoseconds
- detection of beta particles

Plastic scintillators
- scintillation chemicals in plastic matrix
- pulse decay time 1-2 nanoseconds
- contain hydrogen => detection of fast neutrons
- Can be machined into almost any desirable shape and size ranging from thin fibres to thin sheets. They are inert to water air, and many chemicals, and for this reason they can be used in direct contact with the radioactive sample.

Gaseous scintillators
- mixtures of noble gases
- The scintillations are produced as a result of atomic transitions. Since the light emitted by noble gases belongs to the ultraviolet region, other gases, such as nitrogen, are added to the main gas to act as wavelength shifters. Thin layers of fluorescent materials used for coating the inner walls of the gas container achieve the same effect.

VI. Semiconductor Detectors

Principles of Operation

Semiconductor detectors are solid-state devices that operate essentially like ionization chambers. The charge carriers in semiconductors are not electrons and ions, as in the gas counters, but electrons and "holes* ". Radiation incident upon the semiconducting junction produces electron-hole pairs as it passes through it (Fig. 20). Electrons and holes are swept away under the influence of the electric field and, with proper electronics the charge collected produces a pulse that can be recorded.

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*) When an electron moves to the conduction band, an empty state is left in the valence band. This is called a *hole*. A hole is the absence of an electron. When the electron moves in one direction, a hole moves in the opposite direction. Holes are treated as particles with positive charges: *-(-e) = +e*. They contribute to the conductivity in the same way electrons do. In a pure and electrically neutral semiconductor, the number of electrons is always equal to the number of holes.
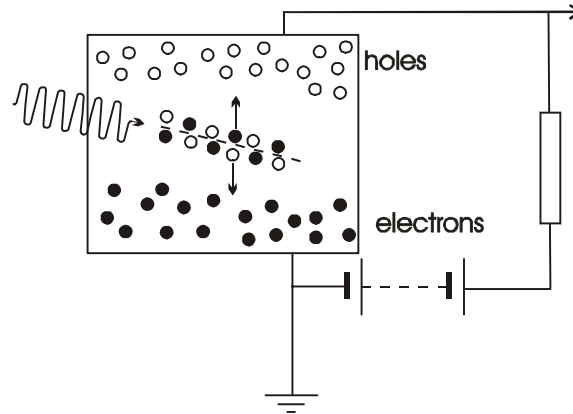
Figure 20 Principle of a semiconductor detector.

The most important advantage of the semiconductor detectors, compared to other types of radiation counters, is their superior *energy resolution*: the ability to resolve the energy of particles out of a polyenergetic energy spectrum. As an example, γ spectra taken with NaI(Tl) scintillator detector and with semiconductor detector are compared in Fig. 21.
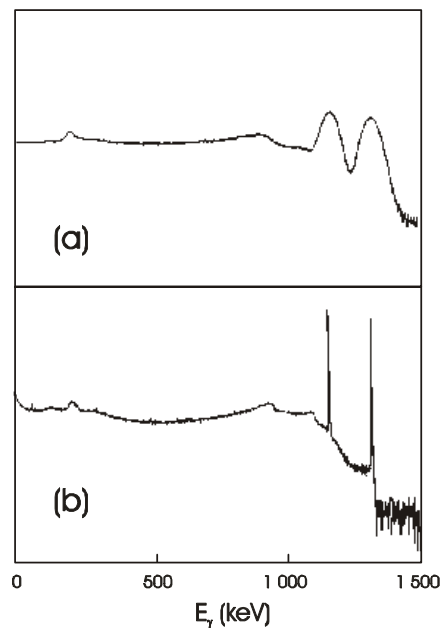

Figure 21 Gamma spectrum of a ^{60}Co radioactive source taken with: (a) scintillation NaI(Tl) detector, and (b) semiconductor GeLi detector.

Types of Detectors

Types of semiconductors detectors:
- surface-barrier detector
  – oxidised high purity Si => p-type surface layer
- diffused-junction detector
  – high purity Si wafer with n-type layer (diffused P) => p-n junction

- silicon lithium-drifted (SiLi) detector
  – formation of n-p junction by Li diffusion
  – increase of the depletion depth by ion drifting
  – after the drifting process has been completed, the detector is mounted on a cryostat and is always kept at a low temperature (77 K)
  – charged particles and X-rays
- germanium lithium-drifted (GeLi) detector
  – the same preparation as SiLi
  – keeping the Ge(Li) detector at a low temperature is much more critical than for Si(Li) detectors => always operated at liquid nitrogen temperature (77 K)
- hyperpure germanium (HPGe) detector
  – high-purity germanium with an impurity concentration of less than 10^{16} atoms/m^3
  – either p-type or n-type
  – volume up to 200 cm^3
  – can be stored at room temperature

Literature

N. Tsoulfanidis, Measurement and Detection of Radiation (Hemisphere Publishing Corporation), Washington 1983
G. F. Knoll, Radiation Detection and Measurement (John Wiley & sons) New York 1989