Nuclear/Particle Detectors

References:

(1) P.J. Ouseph, ***Introduction To Nuclear Radiation Detectors***, (QC787C6088 1975). ***

(2) W.H. Tait, ***Radiation Detection***, (QC787C6T24, 1980). *

(3) W.R. Leo, Techniques for nuclear and particle experiments, 2/e (QC793.46L46, 1994). *

(4) A. Melissinos, ***Experiments in Modern Physics*** (QC33.M52, 1966). **

(5) C.E. Crouthamel (ed.), ***Applied Gamma-Ray Spectrometry***, 2/e (QC490.C7, 1970).

(I) Radioactive Source

A radioactive source contains unstable nuclei of a particular type &
is characterized by

(1) its activity or source strength (A) (= disintegration rate),
(2) the type of radiation (α, β, γ etc.),
(3) the particle (kinetic) energy (T), and
(4) the branching ratio (B) (% of each decay mode).

(II) Interaction of radiation/particle with matter

(A) *Interaction of γ-rays or* x-*rays with matter:*

(read ref. 1 for details)
There are three interaction processes:
(1) photoelectric effect
(2) Compton scattering
(3) pair production (if photon energy > $2m_ec^2$ =1.022 MeV)

As shown in Fig. 1, the total absorption cross-section for gamma rays is

$$\sigma_{total} = \sigma_{photo} + \sigma_{Compton} + \sigma_{pair}$$

where

σ_{photo} = absorption cross-section due to photoelectric effect

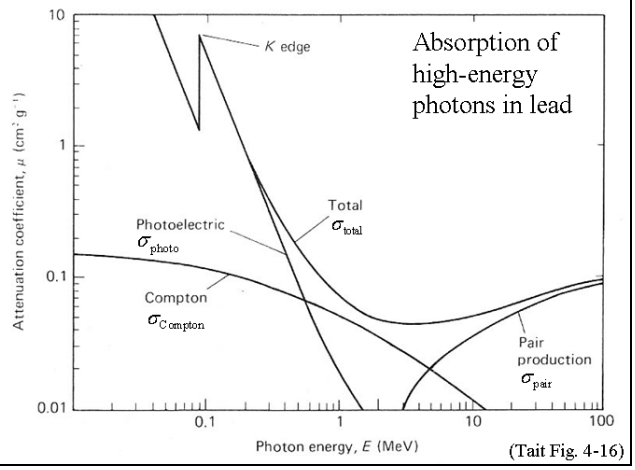
$\sigma_{Compton}$ = absorption cross-section due to Compton scattering

σ_{pair} = absorption cross-section due to pair production

(B) *Interaction of charged particles* (e⁻, p, α, …) *with matter:*

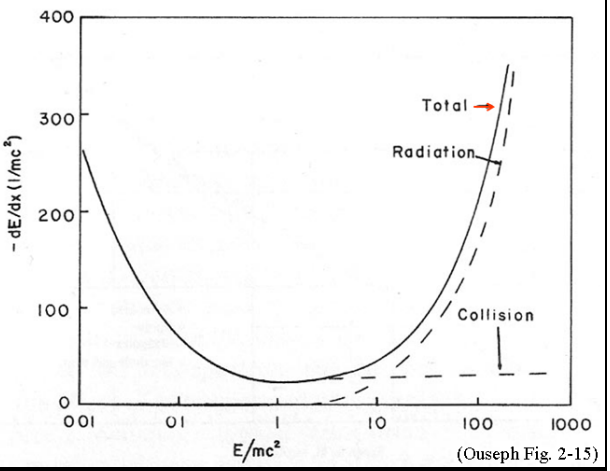
(read ref. 1 for details)
Main processes (Fig. 2) are:
(1) ionization (collision with atomic electrons in matter)
(The charged particle ionizes the matter along its path.)
(2) radiation loss

Fig. 1: Typical absorption curve:



(Tait Fig. 4-16)

Fig. 2: Energy loss for electrons in lead: (E = electron energy)



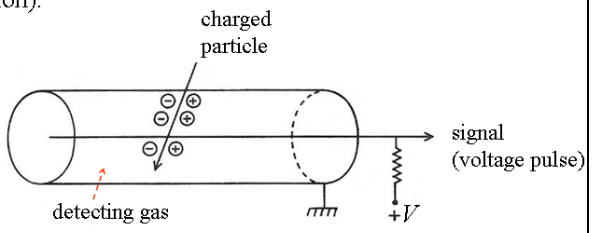
(Ouseph Fig. 2-15)

(III) Detectors

(A) Gas detectors for charged particles

Fig. 3 shows a typical gas filled detector: a cylindrical tube (the cathode, usually grounded) and a central wire (the anode). The incident particle ionizes the gas in the tube (mainly inert gas, but special gas mixture is used for different radiation).

Fig. 3

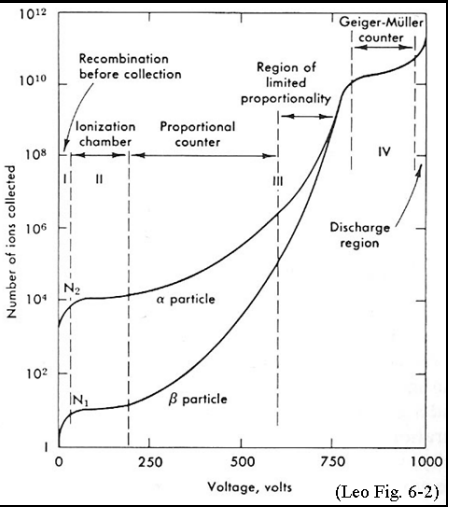


(Ouseph Fig. 3-1)

The produced electrons and ions along the particle track are separated by the electric field set up between the two electrodes. The collection of these charges results in an electric pulse at the wire (for each incident particle).
Electrons move quickly toward the central wire while ions drift slowly toward the cathode. If the voltage is high enough, the electrons (accelerated by the electric field) can gain enough energy for further ionizations. The pulse height is therefore higher for higher V.
Fig. 4 shows different operating regions.
For optimal operation in different regions, the detector electrodes may have different shape for better performance.

(1) Region I: In this low field region, some of the generated electrons and ions can recombine. Then the **gain** $A < 1$.

Fig. 4: The pulse height as a function of the applied voltage (V) for two types of incident particles α & β.



(Leo Fig. 6-2)

(2) Region II: (Ionization chamber region) All electrons and ions generated by the incident particle are collected. $A = 1$. The detector operated in this mode is called an ***ionization chamber***. This detector can be used to measure particle energy which is directly related to the number of electron-ion pairs produced. (To ensure that $A = 1$, ionization chambers are always made with parallel flat plate electrodes.)

(3) Region III: (Proportionality region) For the cylindrical detector shown in Fig. 3, the electric field is given by

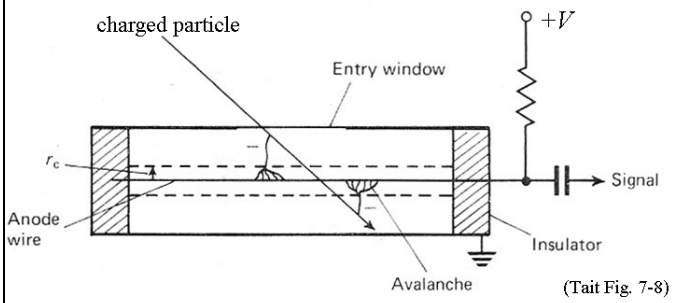
$$E = \frac{V}{rLog(b/a)}$$

where r = distance from the tube axis,
b = cathode radius, and
a = anode wire radius.

If the applied voltage is high and/or the wire is thin, the accelerating electric field is sufficient high near the anode that the electrons can gain enough energy to further ionize the gas. This process may occur many times and a "charge avalanche" can take place close to the anode (at $r < r_c$, the critical radius) where the field is high (Fig. 5).
Therefore the gain $A \gg 1$. Usually $A > 10^3$.

At a fixed V, the pulse height is linearly proportional to the incident particle energy. Therefore the tube can be used as a spectrometer (i.e. an instrument for energy measurement).
If the incident charged particles are monoenergetic, the energy spectrum displays a peak.
The detector operated in this mode is called a ***proportional counter***.

Fig. 5: A side-window **proportional counter**

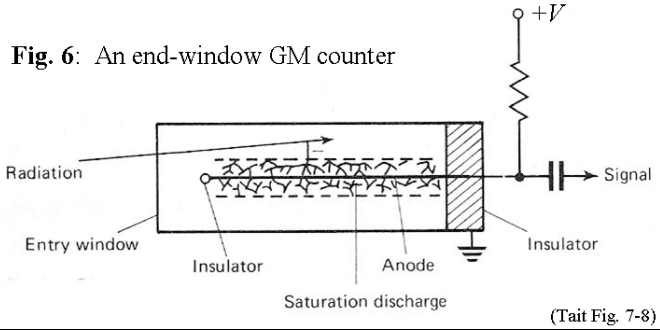


(Tait Fig. 7-8)

Note: In the avalanche discharge, X-rays and UV photons are also emitted. These photons can knock out electrons from the detector wall and the discharge is affected. This photo-ionization process can be quenched by mixing a small amount of organic gas to the detecting gas.

(4) Region IV: (Geiger-Müller region)
Here the applied voltage is so high that a saturation discharge is generated in the entire axial volume within the critical radius. In this mode of counting, the signal pulse is usually quite large (about 1 volt) and external amplification is not

Fig. 6: An end-window GM counter



(Tait Fig. 7-8)

At a fixed applied voltage, the output pulse (corresponding to one incident particle) is independent of the incident particle energy. It cannot be used for energy measurement.
In this mode, the tube is called a ***GM counter***. *A GM tube just counts the number of incident charged particles.*

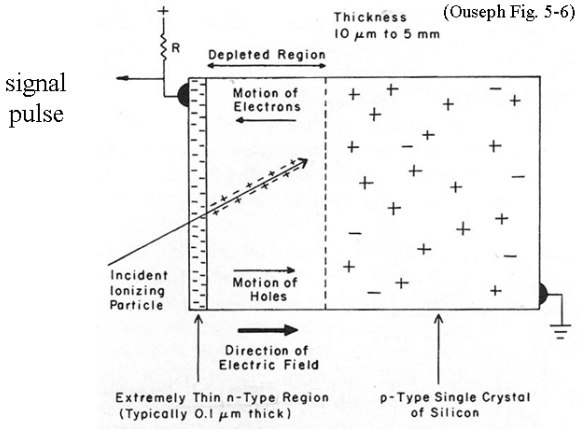
Note: In each discharge, a large number of positive ions will gain sufficiently high energies to knock out electrons from the cathode, the tube wall. These electrons can trigger another discharge and therefore recycle the counter. We can use an external electronic circuit to quench the discharge, (we want one discharge for one incident particle) but it may take more than 10 ms. Internal ion quenching (similar to photon quenching mentioned above) is accomplished by adding about 10% of organic vapor (such as ethanol), or about 1% of a halogen (such as chlorine or bromine) to the noble gas.

The ionization potentials of these quenching agents are substantially less than those of the noble gases. Therefore the quenching gas molecules will pick up the ionization and dissociate. Organic quenching agents are thus gradually used up, imposing a useful lifetime of the order of 10^8-10^9 counts on the detector tube. The halogen molecules can re-associate but they are extremely reactive. The impurities produced limit the tube lifetime to about 10^{10}-10^{13} counts.

(5) Discharge region: When V is increased beyond region IV, breakdowns occur continuously and the tube may be damaged. With special arrangement of supplied voltage, such breakdowns can be made use of for detection of charged particles. This detector is called the ***spark chamber*** which is the main tool in early days of high energy experiments.

(B) Semiconductor detector (for charge particles)
A typical semiconductor detector is a reverse biased p-n junction (Fig. 7). An electric field is built up in the depletion layer where no mobile charge carriers can stay. The ionizations produced by an incident particle (α or β particle) are cleaned up by this field and a pulse (with height linearly proportional to the particle energy) is formed. Since semiconductor of high purity and high resistivity is used, the noise (i.e. the reverse leakage current) is very low. The energy required to create one electron-hole pair in Si is about 3.5 eV, much less than 30 eV in a typical gas detector. Therefore the semiconductor detectors have excellent energy resolution. The detector must be custom-designed (with appropriate window thickness & depletion layer thickness) for different particle type. Semiconductor detectors for x-rays & gamma rays are also available.

Fig. 7 (Ouseph Fig. 5-6)



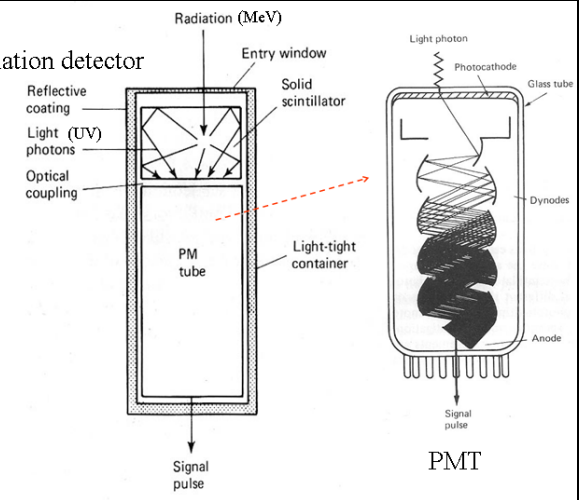
If the incident charged particles are monoenergetic, the energy spectrum displays a peak.

(C) NaI(Tl) scintillation detector (for gamma rays)

(1) ***Interaction:*** Gamma photon interacts with matter mainly in one of the three processes:
(a) the photoelectric effect, (b) Compton effect and (c) the pair production.
Which process is important depends on the photon energy and the absorber as shown in Fig. 1.

(2) ***Detector:*** A scintillation detector (Fig. 8) is composed of a scintillator and a matched photomultiplier tube (PMT). The scintillation detector has the highest detecting efficiency for gamma-rays (very fast response and good stability) and can be used to measure gamma photon energy. It is a gamma spectrometer.
Different scintillators are available. The most common one is NaI(Tl). It is a NaI single crystal doped with Tl.

Fig. 8
Scintillation detector



(3) ***Energy spectrum for a monochromatic gamma source***
A typical spectrum of ^{137}Cs gamma rays (0.662 MeV) measured with a NaI(Tl) detector is shown in Fig. 9. This spectrum displays various complex features, in addition to a simple peak. (If a proportional counter or semiconductor detector is used to detect monoenergetic charged particles, we get a spectrum showing just one simple peak.)

(a) The ***full energy peak*** is due to total energy dissipation of the incident γ photon in the scintillator. The scintillator converts the deposited energy to scintillations (UV photons) which are collected by the PMT. (Typically, about 1000 UV photons are generated in the scintillator for each incident gamma photon.)
Thus the position of full energy peak in the spectrum represents the monochromatic γ energy (E_0).

(b) Note that the rest of the spectrum is mainly due to Compton scattering. Here, the scattered photon escapes from the scintillator & only the scattered electron generated in Compton scattering deposits energy to the scintillator, resulting in UV photons (scintillations) collected by the PMT.

(c) The ***Compton edge*** (E_c) is associated with the 180° Compton backscattering. For 180° backscattering, the energy transfer to the scattered electron is maximum:

$$E_c = E_0 - E_s$$

where $E_s = E_0/(1+2\alpha)$ is the scattered photon energy,

$$\alpha = \frac{E_0}{m_e c^2}$$

This edge is not sharp enough for precise energy measurement.

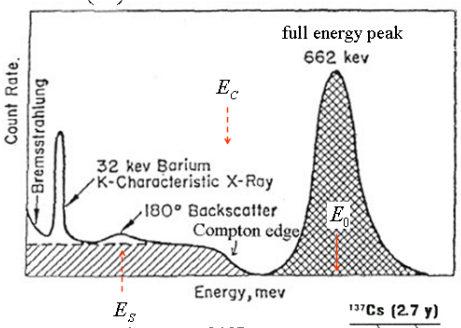
(d) The ***backscatter peak*** at energy E_s also results from 180° Compton backscattering. Here the scattered electron left the scintillator and the scattered photon dissipates energy to the scintillator, resulting in UV photons (scintillations) collected by the PMT.

(e) Because of the statistical nature of all interaction processes, all features in the spectrum are subject to energy broadening. We define the detector resolution as

$$\frac{\Delta E}{E}$$

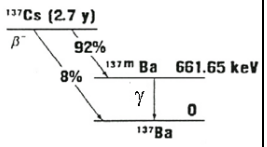
where ΔE is the FWHM (full width at half maximum) of the full energy peak at energy E.

Fig. 9 Energy spectrum of ^{137}Cs gamma rays as detected by a NaI(Tl) scintillation counter.



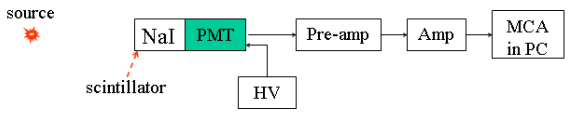
(Ref. 5)

Decay scheme of ^{137}Cs showing β⁻ and γ decays



(IV) Detector electronics

A typical setup of electronics for a scintillation detector:



HV: high voltage power supply
Preamp: preamplifier
Amp: amplifier
MCA: multichannel analyzer
(for determining the energy spectrum)

To reduce background signal, it is simpler to just make use of the full energy peak (Fig. 9) for counting monochromatic photons (with energy E).

Define the peak count rate (n) as the total counts within the full energy peak (P) divided by the counting time (t).
If the source activity (A) is known, then

$$n = A\,B\,G\,\varepsilon_i$$

The correction factors are:
(1) Source factor: B is the branching ratio of the gamma decay for photons with energy E. This mean the source emits photons with energy E at a rate equal to AB.
(2) Geometrical factor (G): The photon emission from the source is isotropic and only a fraction is incident on the detector crystal surface:

$$G = (\pi r^2)/(4\pi h^2)$$

where r is the radius of detector surface facing the source, and h is the distance from the point source to the detector surface.

(3) Detector efficiency (ε_E) and peak efficiency (ε_i): Not all photons incident on the scintillator crystal can be detected. When monochromatic γ photons are incident on the scintillator crystal, only a fraction ε_E interacts to produce measurable scintillations & even a smaller fraction ε_i to result in counts within the full energy peak. ε_i depends on photon energy and crystal size. Their values can be calculate and tabulated in Ref.5.