Detector Physics

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Physics of Atomic Nuclei
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General Detector Properties

The incoming particle must interaction in the material. This interaction leads to the production of a charge Q at time t=0.

The charge is collected by imposing an electric field within the detector material. Positive and negative charges will flow in opposite directions.

Time required for charge collection will depend on the ion (electron or hole) mobility and the distance the charges must travel.

Idea is that the amount of charge deposited can be used to characterize the incoming particle

Particle Interactions in Detectors

The operation of any radiation detector depends on the manner in which the incoming particles interact with the detector material

Heavy charged particles
Fast electrons
Neutrons
X-rays and gamma rays

Charged particles (including electrons) will interact with electrons present in the detector material through the atomic collisions.

Neutrons, X-rays and gamma rays are uncharged, and undergo a more "catastrophic" (often nuclear) interaction that alters the properties of the incident radiation

Heavy Charged Particles

Primary interaction is via atomic collisions between the positively-charged heavy ion and the negatively-charge orbital electrons within the detection medium.

The maximum energy that can be transferred is

$4Em_e/m$

Where m and E are the particle mass and energy, respectively, and m_e is the electron mass. Since m_e is much smaller than the incoming particle mass, the energy transfer is small.

primary particle loses its energy over MANY interactions

produce many excited atoms or ion pairs in the detector material

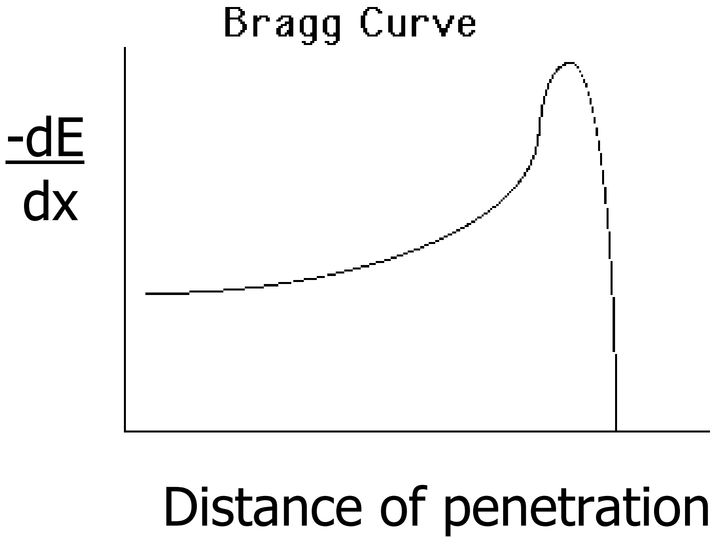
Stopping Power

The linear stopping power for charged particles is given as

$$S = -dE/dx$$

Through the Bethe formula, the linear stopping power is a function of the atomic number of the stopping material (Z) and the ion charge (z) and velocity (v) of the incident particle

$$S \propto (z/v)^2 NZ$$



Fast Electrons vs. Heavy Ions

Fast electrons lose energy at a lower rate and follow a more torturous path through absorbing materials. This can be attributed to the low ion charge ($z = 1$) and low mass of the electron.

Fast electrons can also lose energy through radiative processes

$S \propto (1/v)^2 NZ$ (collisional)

$S \propto NEZ^2$ (radiative)

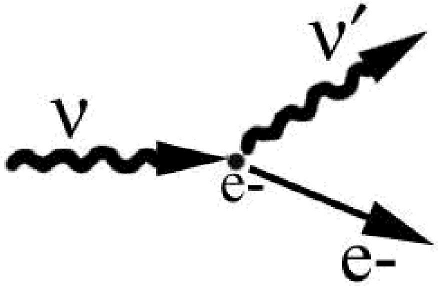
Therefore the radiative loses are most important for high energy electrons where the absorbing material has a large atomic number.

X-rays and Gamma Rays

Both X-rays and gamma rays carry no charge. There three major types of interactions for photons in an absorbing material are:

Photoelectric absorption – photon completely disappears. This process dominates at low energy. Electrons ejected from constituent atoms of absorber.

Compton scattering –



Pair production – if the photon energy exceeds 1.02 MeV, e^+e^- production energetically possible. Predominate for high energy gamma rays. Also results in the production of secondary phonon (annihilation radiation).

Neutron Detection

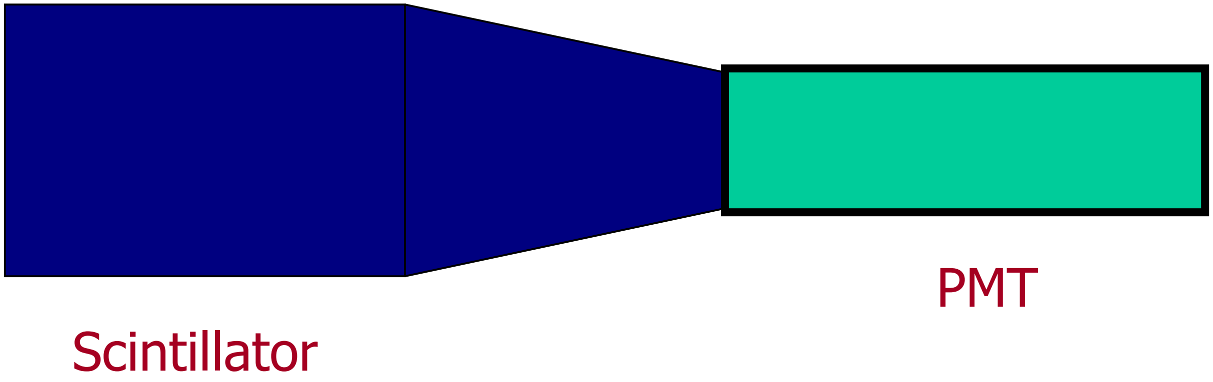
Since the neutron carries no net charge, the major interactions in an absorbing material are:

Neutron scattering – scattered nucleus is excited and emits a photon. Employed for fast neutron ($E_n > 0.5$ MeV) detection.

Neutron induced reactions – secondary particles following reaction are detected (e.g., gamma rays, protons, or alpha particles). The reaction must be energetically possible. Reaction processes are favored for slow neutron ($E_n < 0.5$ MeV) detection.

Cosmic Ray Detector

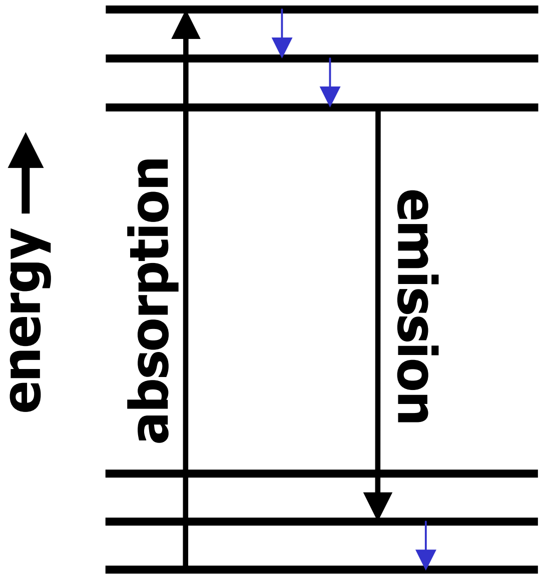
For the cosmic ray detectors you will assemble, the detector has two components: a plastic scintillator and a photomultiplier tube. Cosmic ray particles will interact within the scintillator and produce a light pulse. The photomultiplier tube converts the light pulses into an electrical signal. A pulse mode circuit will be used to produce a voltage that can be read-out to characterize the interacting radiation.



Organic Scintillators

Properties of good scintillators

- high conversion efficiency
- conversion is linear (E $\propto$ # photons)
- transparent to own emission
- decay time short
- good optical quality and easy to work with
- index of refraction near glass ($n = 1.5$)



Fluorescence

Types of organic scintillators

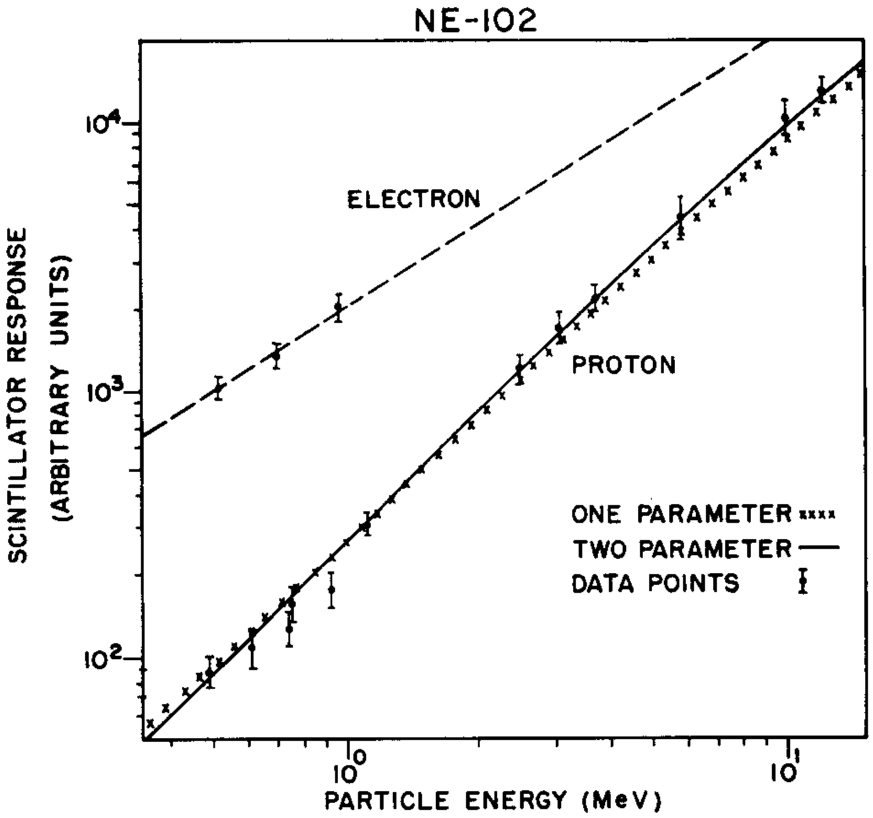
- **pure organic** – anthracene and stilbene
- **liquid organic** – organic dissolved in appropriate solvent
- **plastic scintillator** – organic dissolved in solvent and then polymerized

NE102 Plastic Scintillator

NE102 is one of the most common plastic scintillator material. It has applications to gamma, alpha, beta and fast neutron counting.

Properties of NE102

- λ_{max} = 423 mn
- light output 65% of anthracene
- decay constant 2.4 ns
- refractive index 1.581
- softening point 75 ºC
- density 1.032 g/cm^3
- H/C atom ratio 1.104



Photomultiplier Tubes (PMTs)

A PMT has two main components, a photocathode and electron multiplier, which will result in the production of $10^7 - 10^{10}$ electrons per photon pulse.

Photocathode – photon strikes a metal surface, releasing an electron

$E_{h\nu} = \phi + E_{e-}$

ϕ is the work function for the metal

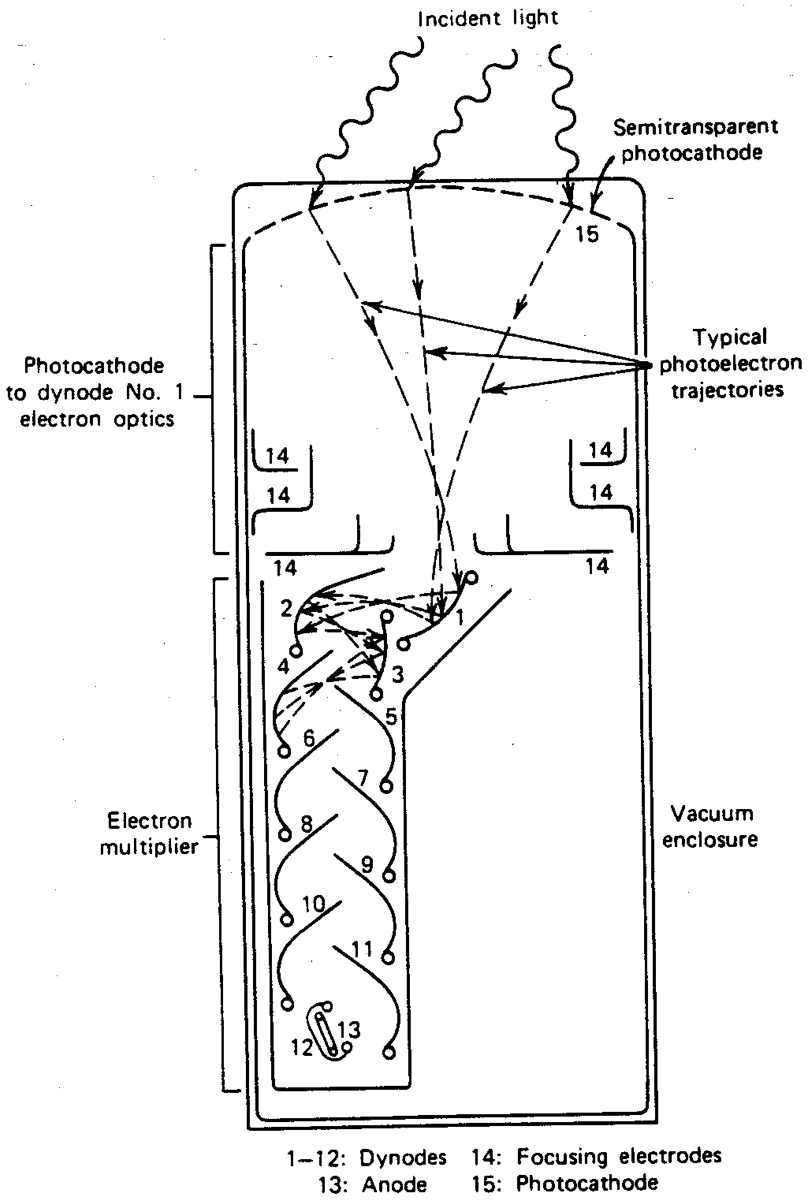
$E_{e-} \sim 1$ keV

Typical photocathode materials are bialkali metals (K_2CsSb, Na_2KSb) which have quantum efficiencies ~ 25%

Electron multiplier – accelerated electron strikes dynode (BeO, MgO, Cs_3Sb), releasing multiple electrons

δ = multiplication factor = # secondary e-/ primary e-

Basic Elements of a PMT

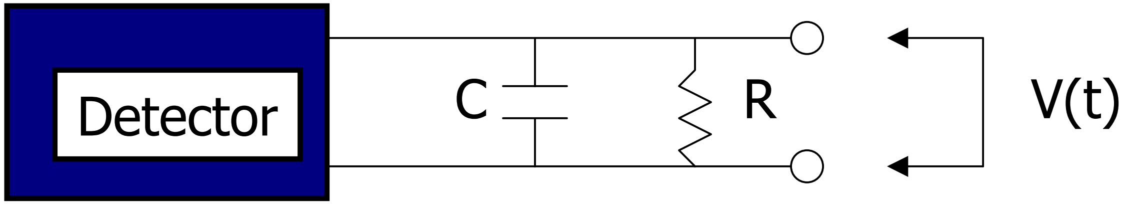


Shown to the left is a PMT with a focused linear dynode structure. The overall gain of any PMT is given as

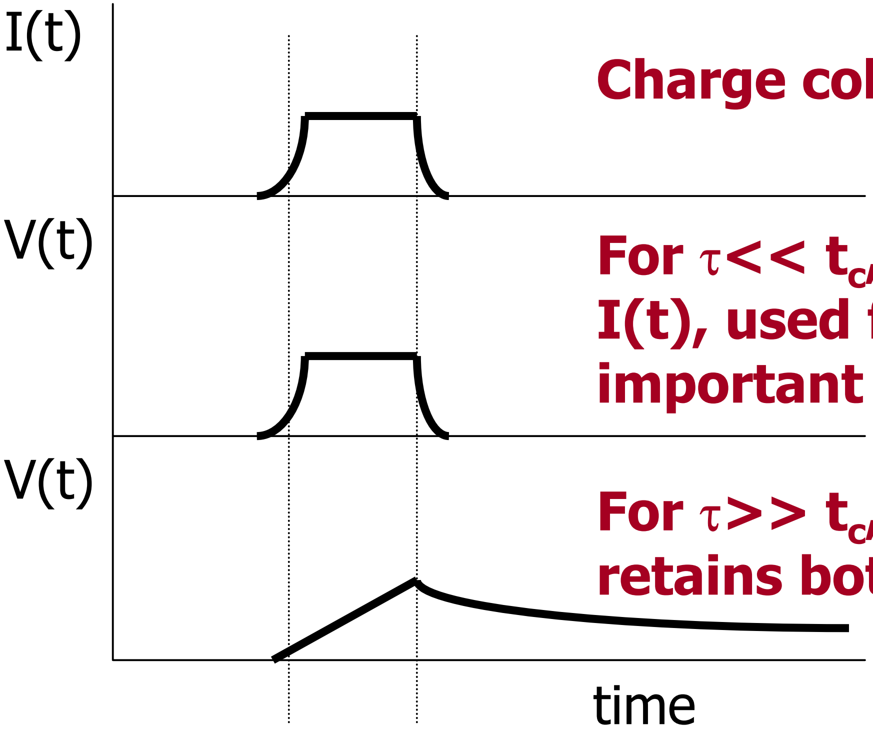
$$\alpha\delta^N$$

N = number of stages
α = fraction of all photoelectrons collected

Pulse Mode Operation



Time constant for circuit τ = RC, where R is the resistance value and C is the total capacitance $C = C_{detector} + C_{cabling} + C_{circuit}$



Charge collected is area under curve

For $\tau << t_c$, shape of V(t) is nearly identical to I(t), used for high event rates or if timing important

For $\tau >> t_c$, $V_{max} = Q/C$. Each individual event retains both amplitude and time

References

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"Introductory Nuclear Physics," Kenneth S. Krane (John Wiley and Sons, New York, 1988)

"Introductory Nuclear Physics," (2nd edition) Samuel S.M. Wong (John Wiley and Sons, New York, 1998)

"Techniques for Nuclear and Particle Physics Experiments," (2nd edition) W.R. Leo (Springer-Verlag, Berlin, 1994)

www.rstp.uwaterloo.ca

hyperphysics.phy-astr.gsu.edu/hbase/mod3.html

www.cosmic-ray.org

Additional slides

Cosmic Radiation

The primary components of cosmic radiation are extremely high energy charged particles and heavy ions.

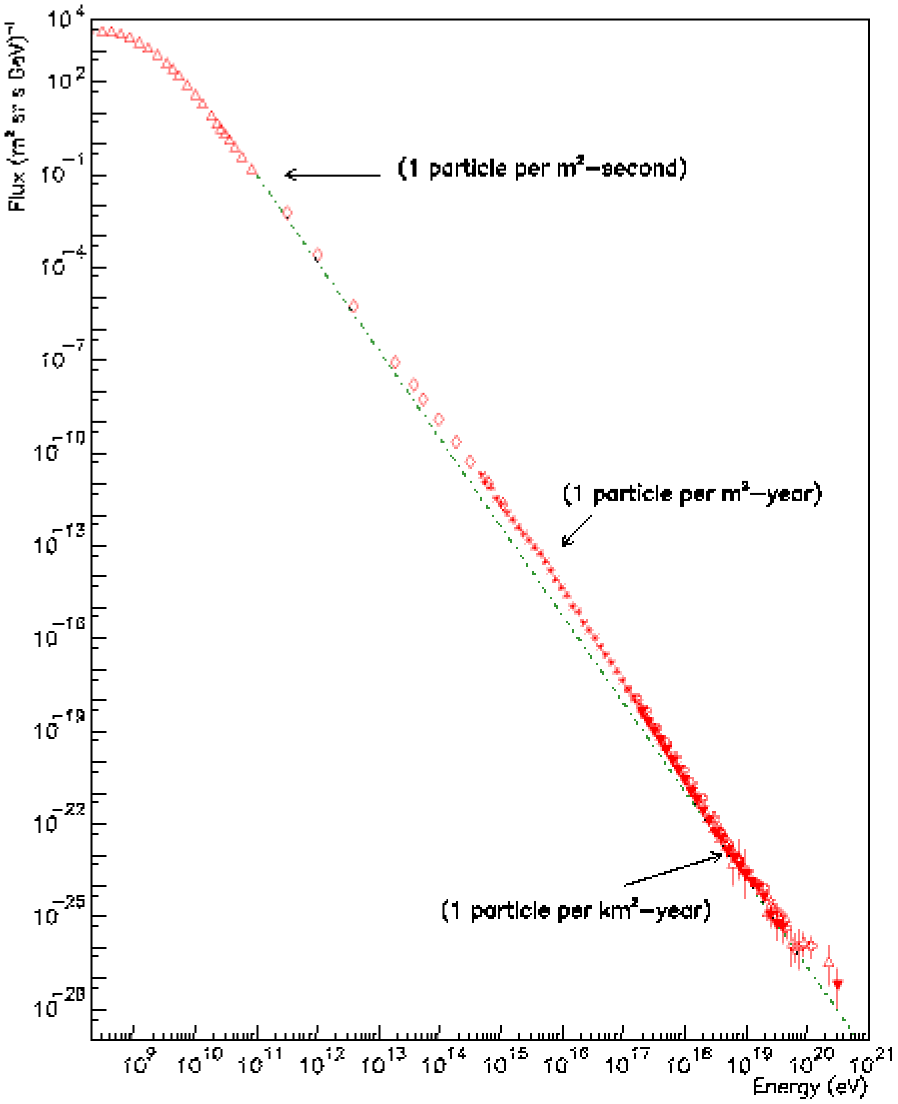
These particles interact in the earth’s atmosphere, producing a wide variety of secondary radiations:

electrons and muons
pions
protons and neutrons
electromagnetic photons

Only the very penetrating charged particles make it down to the surface of the earth

typically the highest energy electrons and muons

Cosmic Ray Energy Spectrum



Cosmic rays have been observed with energies from $10^9 - 10^{21}$ eV

Flux of cosmic rays follows a single power law (E^{-3})

Two noticeable structure

"knee" at 10^{15} eV

"ankle" at 10^{18} eV

Properties of Some “Elementary” Particles

Symbol	Name	Charge	Rest Mass (amu)	Spin
γ	**Photon**	**0**	**0**	**1**
e-	**Electron**	**-1**	**0.0005486**	**1/2**
e+	**Positron**	**+1**	**0.0005486**	**1/2**
ν	**Neutrino**	**0**	**<2 x 10-7**	**1/2**
$\mu^{\pm}$	**Muon**	**±1**	**0.1134**	**1/2**
$\pi^{\pm}$	**Pion**	**±1**	**0.1498**	**0**
π^{0}	**Pion**	**0**	**0.1449**	**0**
p	**Proton**	**+1**	**1.0072765**	**1/2**
n	**Neutron**	**0**	**1.0086650**	**1/2**

Modes of Detector Operation

Current mode – typically used for applications involving high counting rates, the average of individual current bursts serves as the basic signal recorded

$$I_0 = (\text{event rate})(\text{charge produced})$$

Mean square voltage mode – used to enhance signals produced by an event which produces large charge response in the detector

$$I \propto (\text{event rate})(\text{charge produced})^2$$

Pulse mode – most common method, as it preserves information on both amplitude and timing of individual events.

$$V_{max} \propto (\text{charge produced})$$