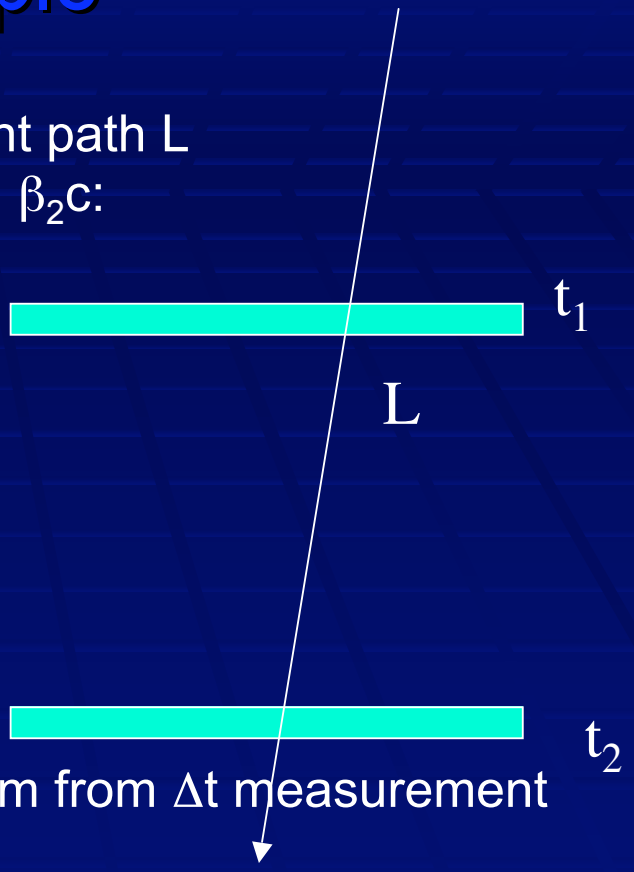
PID: ToF principle

It requires very good time resolution and a sufficient path L
Given 2 particles m_1 and m_2 with velocities $\beta_1 c$ and $\beta_2 c$:

$$\Delta t = t_1 - t_2 = \frac{L}{\beta_1 c} - \frac{L}{\beta_2 c} = \frac{L}{c}\left(\sqrt{1+\frac{m_1^2 c^2}{p^2}} - \sqrt{1+\frac{m_2^2 c^2}{p^2}}\right)$$



Since from $p = \gamma m v = \gamma m \beta c$ and $E = \gamma m c^2$

$$\frac{1}{\beta} = \frac{E}{pc} = \frac{\sqrt{p^2c^2 + m^2c^4}}{pc} = \sqrt{1+\frac{m^2c^2}{p^2}}$$

Given a beam of particles with the same momentum from Δt measurement we separate the 2 species
In our example: given one particle crossing two scintillators if we know p and measure Δt and L we get m

$$\Delta t = t_1 - t_2 = \frac{L}{\beta c} = \frac{L}{c}\sqrt{1+\frac{m^2c^2}{p^2}}$$

Scintillators in brief

Convert energy deposited by a charged particles or high energy photons into light: atoms or molecules of the scintillating medium are excited and decay emitting photons which are detected and converted into electric signals (PMTs)

Scintillating materials:

- organic: aromatic hydrocarbon compounds, solid crystals, plastics or liquids, typically they are faster but have lower light yield.
- inorganic: ionic crystals doped with activator centers or glasses; typically they have larger light yields

Two types of light emission:

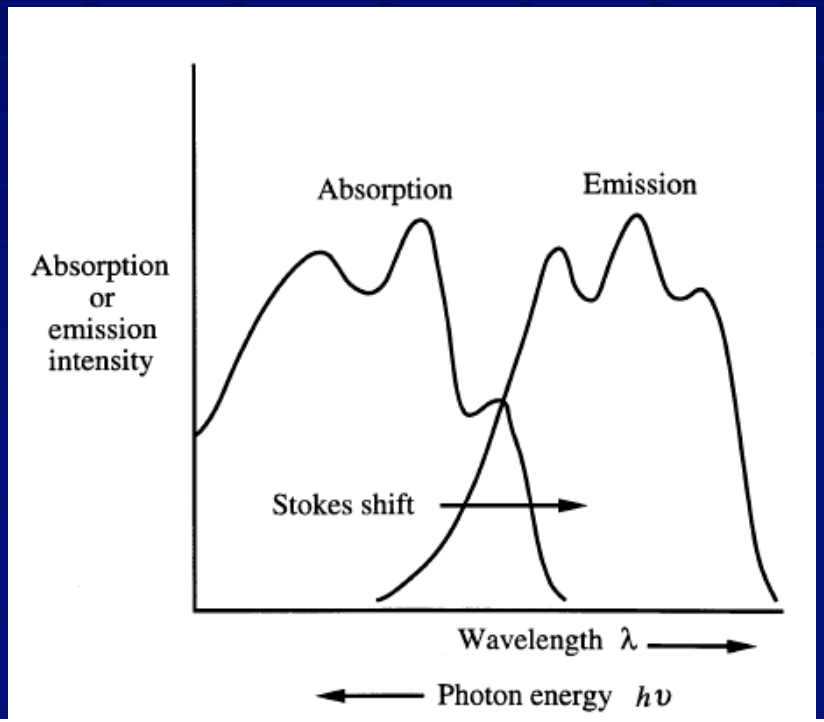
- Fluorescence: prompt ns → μs in visible wavelength range, temperature independent (component useful for particle detection)

- Phosphorescence: emission over longer period μs → ms, hrs with longer wavelength and temperature dependent

Properties of scintillators

Parameters characterizing scintillators:

- Efficiency R_s = average n. of emitted photons/energy of incident radiation
- Scintillation yield = R_s $h\nu$ $h\nu$ = energy of emitted photons
- Time response: depends on decay time of fast component
- the scintillator should be transparent to its own scintillation light (Stokes' shift: the emission wavelength is longer than absorption one)
- linearity



Organic scintillators

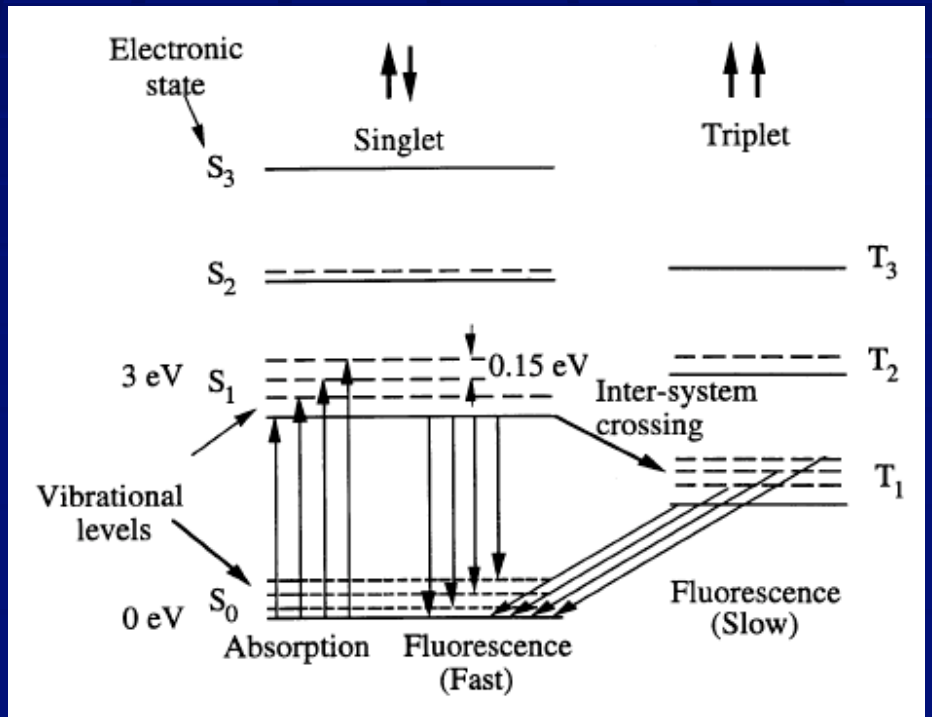
Organic scintillators (plastics or liquids) are composed of aromatic hydrocarbon compounds. Plastic ones are non-fluid solutions consisting of fluorescent organic compounds dissolved in a polymer matrix. Liquid scintillators are fluid solutions with similar fluorescent compounds. No crystal structure is needed.

The emission of light is due to excitation of molecular levels in a primary fluorescent material that emits UV light during de-excitation. This light is absorbed in most organic materials with an absorption length of ~mm. The extraction of a light signal becomes possible only by introducing a second fluorescent material in which the UV light is converted into visible light (wavelength shifter).

Organic scintillators are typically made of low Z materials and have low density. Hence the main interaction >20keV process is not photoelectric absorption (such as in the case of inorganic scintillators) but Compton scattering.Typically, because of the low density more volume is required to obtain a reasonable detection efficiency, but they have low cost.

Organic scintillators

Energy levels of organic scintillators: at room T_a (KT_a = 0.025 eV) electrons on ground state, incident radiation excites electrons to S_1 states, radiationless decays to base S_1 state, emission of light to S_0. S_1 can decay to a triplet state with lower energy and longer decay time. The fluorescence UV light (250-370 nm) is absorbed by most organic materials, so the light signal can be extracted using a second fluorescent material (wavelength shifter) that converts UV in visible light (320-500 nm)



Time dependence of emitted light

Non-radiative transfer of energy from vibrational states to fluorescence state S_1: 0.2-0.4 ns

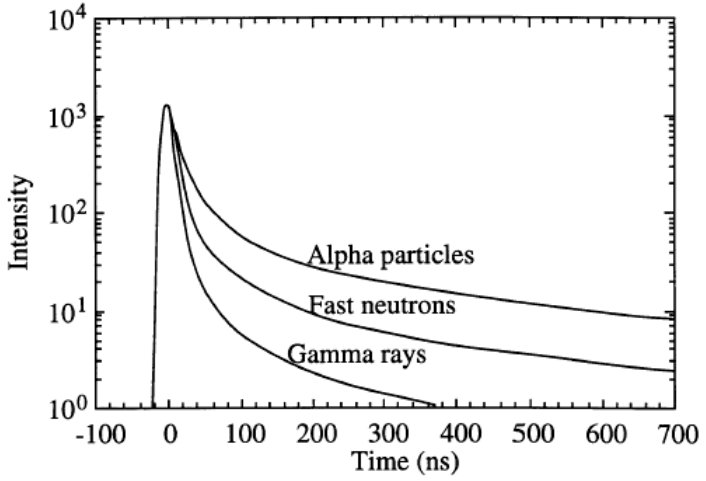
Decay of fluorescent state: 1-3 ns $I(t) \propto 1 - e^{-t/\tau_r}$ τ_r = rise time constant

Fall with time constant τ_f $I(t) \propto e^{-t/\tau_f}$

Material	State	λ_{max} [nm]	τ_f [ns]	ρ [g/cm^3]	photons/MeV
Anthracene	crystal	447	30	1.25	$1.6 \cdot 10^4$
Pilot U	plastic	391	1.4	1.03	$1.0 \cdot 10^4$
NE104	plastic	406	1.8	1.03	$1.0 \cdot 10^4$
NE102	liquid	425	2.6	1.51	$1.2 \cdot 10^4$

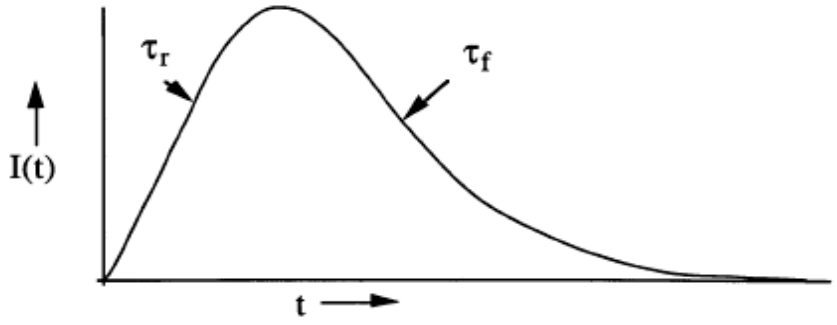
The decay time depends on the ionization density

Decay time in stilbene for various particles



total pulse shape

$$I(t) = I_0(e^{-t/\tau_f} - e^{-t/\tau_r})$$



Birk's law

For organic scintillators the relation between emitted light and energy loss is not linear. Deviations from linearity are due to quenching interactions between excited molecules created along the ionizing particle path absorbing energy

For an ideal scintillator and low ionization density

Luminescence $\propto$ Energy dissipated in scintillator

$$L = SE \qquad \text{or} \qquad \frac{dL}{dr} = S\frac{dE}{dr}$$

The light output depends on the ionization density

$$\frac{dL}{dr} = \frac{S\frac{dE}{dr}}{1 + kB\frac{dE}{dr}}$$

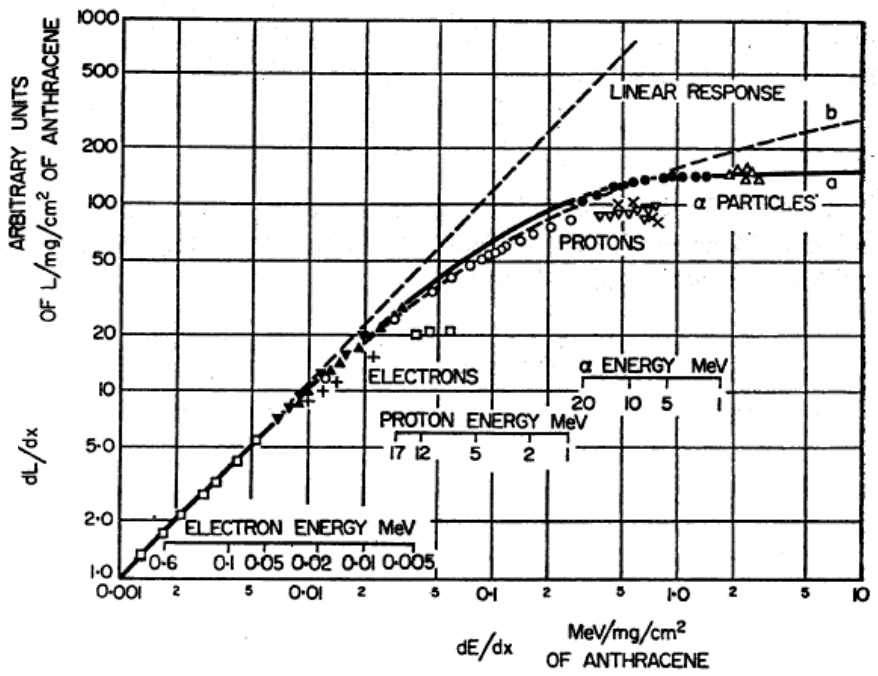
Density of ionized and excited molecules along track

Quenching parameter

For small dE/dr this yields the luminescence yield postulated above.

For large dE/dr the specific luminescence saturates, as indicated by the data.

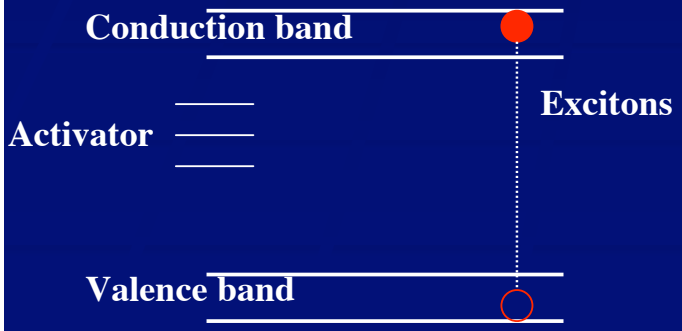
$$\frac{dL}{dr} = \frac{S}{kB} = const$$



Inorganic scintillators

They are usually made of high Z materials and have a fairly high density. The high Z enhances the photoelectric interaction contribution and the high density increases the interaction efficiency. They are crystals grown in high temperature furnaces and are made of Alkali Halides (ie. NaI, CsI) or Oxides (eg. BGO). They have scintillation properties by virtue of their crystalline structure that creates the energy bands between which electrons can jump. Some crystals need activators to enable emission in the visible (eg Thallium which is used in the most frequently used inorganic scintillator NaI(Tl). Ionizing particles produce free electrons, holes and couples of electron-holes (excitons). These move around the crystal lattice until they meet an activator center that they transform into an excited state A* of energy E_1 that can decay emitting light. The decay time depends on the temperature as $\exp[-E_1/(KT)]$

Energy level of a ionic crystal doped with an activator

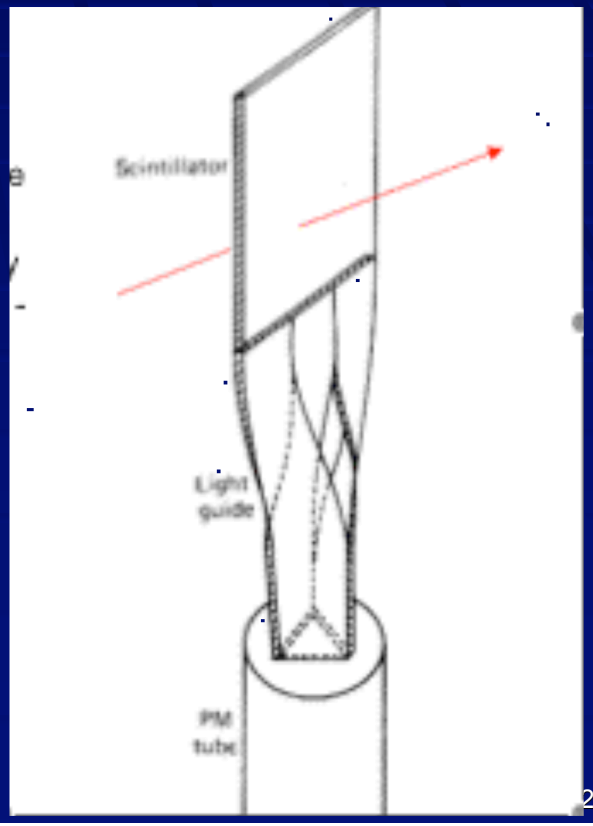


Material	Form	λ_{max} (nm)	τ_f (ns)	ρ (g/cm^3)	Photons per MeV
NaI(Tl) (20°C)	crystal	415	230	3.67	38,000
pure NaI (-196°C)	crystal	303	60	3.67	76,000
$Bi_4Ge_3O_{12}$ (20°C)	crystal	480	300	7.13	8,200
$Bi_4Ge_3O_{12}$ (-100°C)	crystal	480	2000	7.13	24,000
CsI(Na)	crystal	420	630	4.51	39,000
CsI(Tl)	crystal	540	800	4.51	60,000

Scintillators coupled to PMTs

A plastic light guide couples the large cross section scintillator to the small area PMT. The light emitted by the scintillator is transported to the photocathode through the light guide through total internal reflections (when the incident angle is larger than the critical one $\theta_c = \sin^{-1} (n_{med}/n)$ n_{med} =1 for air)
Typically fractions of trapped light are around 20%, the scintillator and light guide may be wrapped of Aluminium foil to prevent leaks of light escaping internal reflections. They are wrapped of black layers to prevent outside light to enter.

The first PMT was built in 1913 by Elster and Geiter
RCA made them commercial Iin 1936



Spectral regions and Units

Wavelength (nm)	Spectral range	Frequency (Hz)	Energy (eV)
	X-ray		
	Soft X-ray		
10			10^{2}
	Extreme UV	10^{16}	
100			10
	UV	10^{15}	
350			
	Visible		
750			
1000	Near IR		
10000	IR		10^{-1}
		10^{13}	
	Far IR	10^{12}	
10^{6}			10^{-3}

Phototubes

http://sales.hamamatsu.com/assets/applications/ETD/pmt_handbook_complete.pdf

Transform a light signal into an electric one: photons hitting the thin photocathode layer of an evaquated glass or quartz tube extract photoelectrons (photoelectic effect)

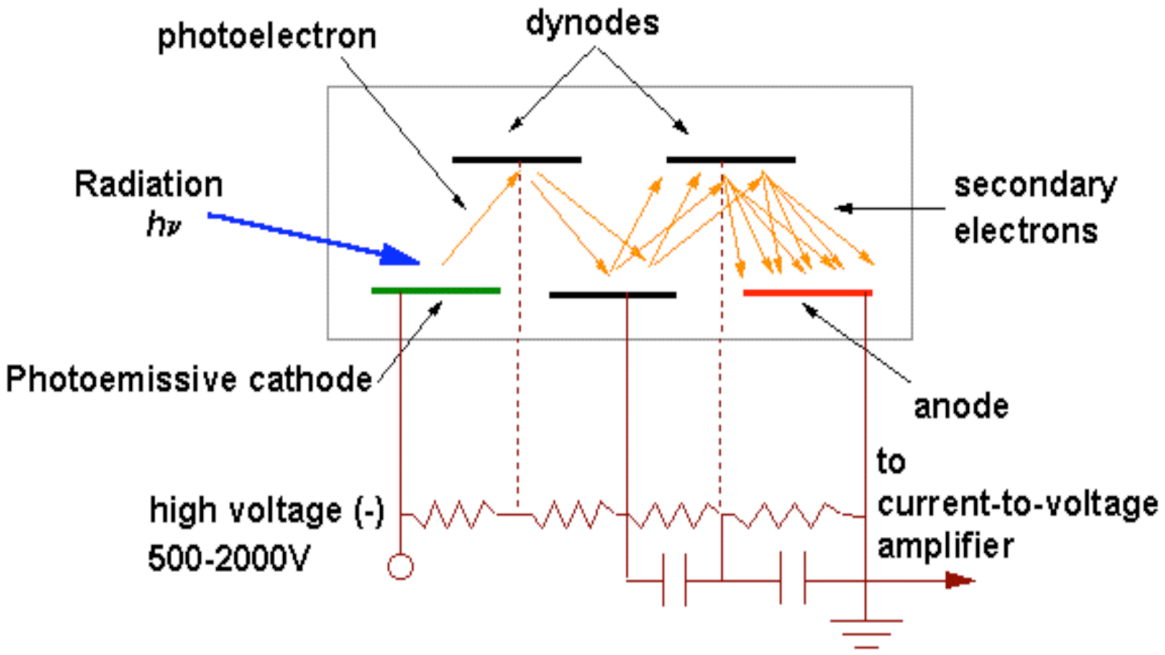
The energy of the emitted electron is $E = h\nu - \Phi$, ν = frequency of photon and Φ = work function of the photocathode

Photocathodes are semiconducting alloys containing 1 or more metals from the alkali group (Na, K, Cs) and materials from group V (eg Sb - antimony).

Bialkali cathodes are made of 2 alkali components.

QE(ν) = #pe emitted by the photocathode/incident photons ~ 20-25% at maximum (λ ~100-1200 nm)

ANTARES
10 inch Hamamtsu 14 stages



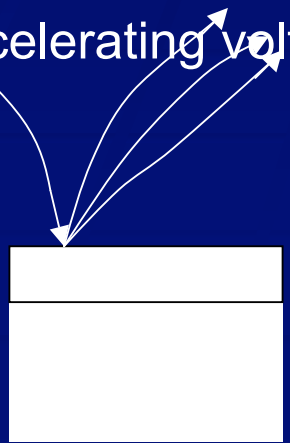
Dynode structures

The collection efficiency of the 1st dynode = # of electrons hitting it/#of emitted photoelectrons ~ 60-90%

Secondary emissive materials used for dynodes are alkali antimonide, Be or Mg oxyde (BeO). Gallium phosphide (GaP) and gallium arsenide phospied.

δ=secondary emission ratio= #of secondary e^- per primary e^-

Varies for various materials as a function of the accelerating voltage of primary e^-



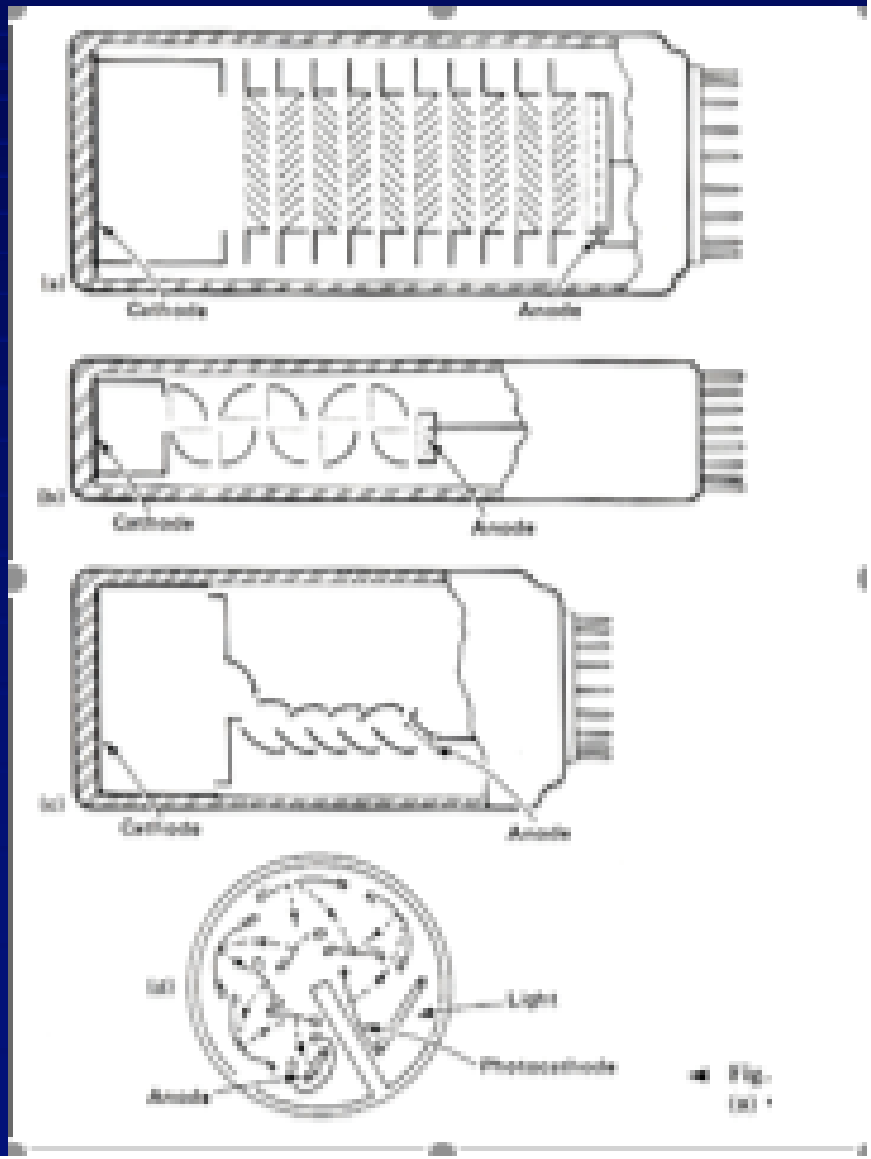
Secondary emissive surface

Circular cage

Venetian blind

Box and grid

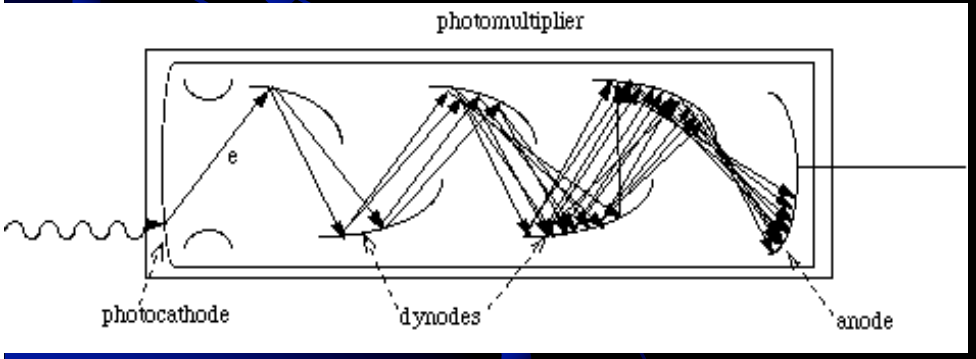
Linear-focused



Photosensors

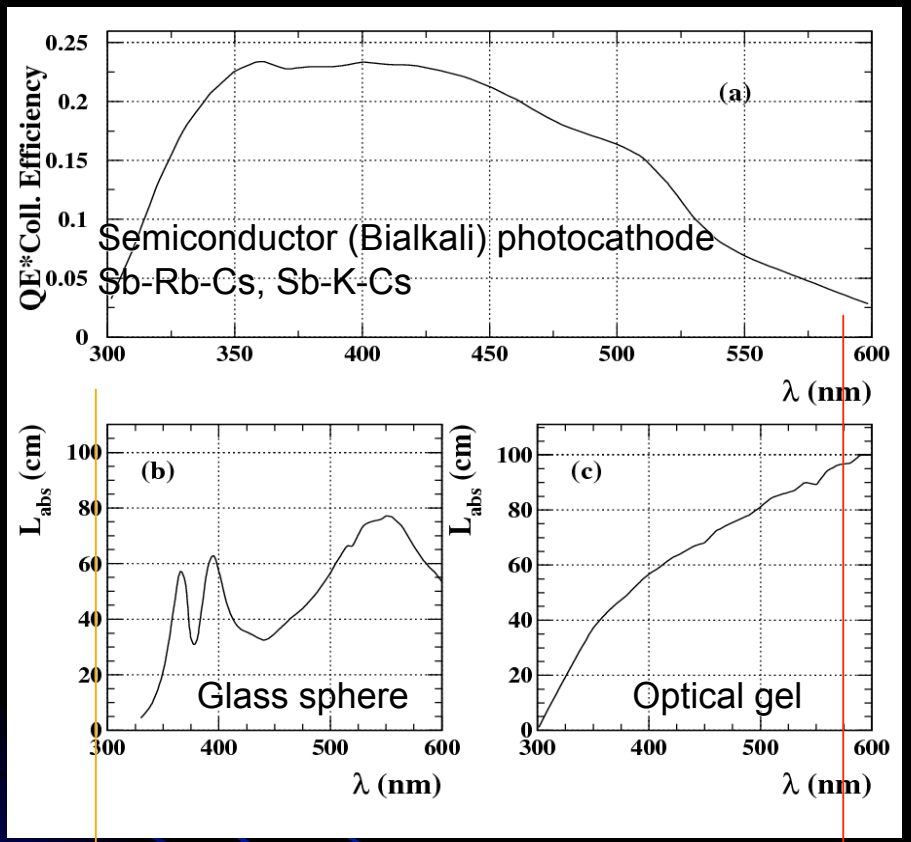
IceCube
10 inch Hamatsu 10 stages

Gain $\propto V^{KN}$ N = # dynodes
K = 0.7-0.8 depends on structure and material of electrodes



pe's undergo an amplification hitting the dynodes Dynodes are made of materials with high secondary electron emission (BeO, Mg-O-Cs) and are kept at potential differences (150-200 V) that accelerate electrons. Multiplication of the number of electrons can reach up to 10^8.
This charge of 10^8 x 1.6 10^{-19} C ~ 2 10^{-11} C arrives at the anode in a time interval ~ 5 ns $\Rightarrow$ I = 4 mA. If the anode is connected to ground via a R = 50 W $\Rightarrow$ a pulse of 200 mV is formed. While the rise time of the pulse is ~2 ns the transit time in the tube is ~ 40 ns and the Transit Time Spread (spread in times of propagation of electrons from the photocathode to the first dynode due to the distribution of the velocity of emitted pe and to the different pathlengths Tyically < 3 ns).

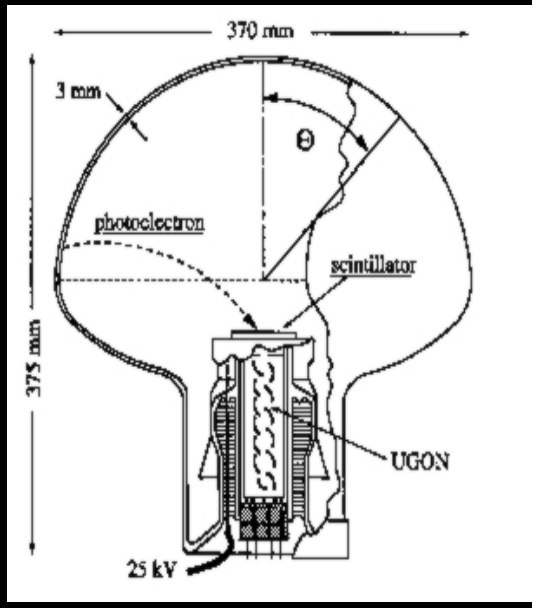
Photosensors for Neutrino Telescopes



Time response: depends on electrode structure and supply voltage

Linearity: linear response of anode current vs incident light intensity

Smart ideas:
Baikal QUASAR



Short wave length limit
Determined by window material

Long wave length limits: determined by photocathode material
hν too small to extract pe

http://sales.hamamatsu.com/assets/applications/ETD/pmt_handbook/pmt_handbook_complete.pdf

Parameters for selecting PMTs

Incident light conditions	
Light wavelength	Window material Photocathode spectral response
Light intensity	Number dynodes Dynode type Voltage applied to dynodes
Light beam size	Effective diameter (size) Viewing configuration
Speed of optical phenomenon	Time response

To which follows the selection of the circuit conditions: signal processing method (analog or digital method) and of the bandwidth of associated circuit

New applications

Main drawbacks of PMTs are the bulky shape, the high prize and the sensitivity to magnetic fields.

Photodiodes are semiconductors light sensors that generate a current or voltage when light illuminates the p-n junction. Allow detection of light in 200-1150 nm)

PIN photodiodes are Near IR detectors (InGaAs or Si) have excellent linearity with light, high speed, low noise and dark current but major drawback: low gain.

Avalanche Si photodiodes (APDs) have internal gain so are more sensitive and have much higher QE > 70%.

A = absorption region where there is an electric field that separates the generated electron-hole pairs and sweeps one carrier towards M = multiplication region. Here there is a high field that guarantees a high gain through impact ionization

G = 100 in Si APDs, 10-40 in Ge or InGaAs

G is limited by statistical fluctuations of avalanche multiplication

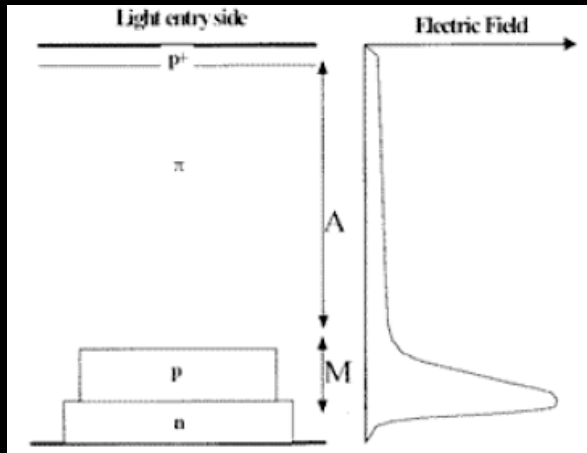


Figure 1: Reach-through APD Structure (Not to Scale)

http://optoelectronics.perkinelmer.com/content/whitepapers/AvalanchePhotodiodes.pdf

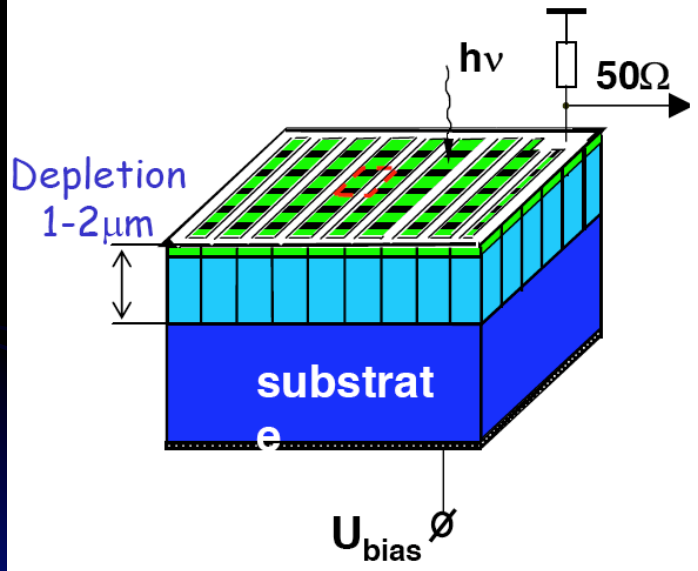
Avalanche PhotoDiodes

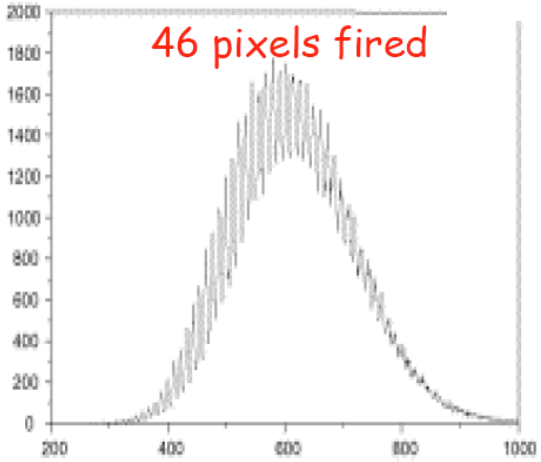
- Operate a specially designed photodiode in reverse high voltage; a photon can induce a avalanche cascade of electron hole creation which is amplified in the strong field.
- Advantages of Avalanche photodiodes
  - very high quantum efficiency of more than 90% possible
  - very good time resolution: < 1 nsec
  - hig bandwidth
  - excellent photon counting resolution due to very large amplification (PMT limited by poisson statistics on the first dynode gain)
- Disadvantages or limitations:
  - Size: typically a few, up to 5 mm in diameter
  - Read the fine print of operational characteristics

Silicon PMTs (Dolgoshein et al)

- FIRST STEP: SINGLE PHOTON AVALANCHE DIODE (SPAD), based on single pixel ➔"photon counter"
- SECOND STEP: from SPAD to

Silicon Photomultiplier (SiPM)





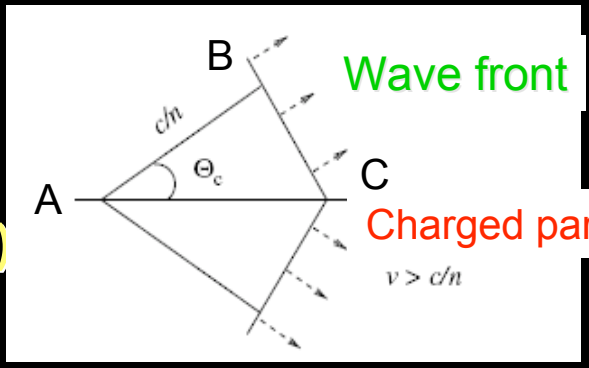
Pixel size ~20-30μm

Multipixel (typically ≤ 1 mm²) Geiger mode photodiode with common readout

Main problem inter-pixel cross-talk
Fast Geiger discharge development < 500 ps
Pixel recovery time ~ 20 ns

The Cherenkov effect

A charged particle traveling in a dielectric medium with n>1 radiates **Cherenkov radiation** if its velocity is larger than the phase velocity of light **v>c/n or β > 1/n (threshold)**



The emission is due to an asymmetric polarization of the medium in front and at the rear of the particle, giving rise to a varying electric dipole momentum.

Some of the particle energy is converted into light. A coherent wave front is generated moving at velocity v at an angle Θ_c

If the media is transparent the Cherenkov light can be detected.

If the particle is ultra-relativistic β~1 Θ_c = const and has max value

$$\cos\theta_c = \frac{AB}{AC} = \frac{\frac{c}{n}t}{\beta ct} = \frac{1}{\beta n}$$

In water Θ_c = 43˚, in ice 41˚

The Cherenkov effect

The intensity of the Cherenkov radiation (number of photons per unit length of particle path and per unit of wave length)

$$\frac{d^2N}{dxd\lambda} = \frac{4\pi^2 z^2 e^2}{hc\lambda^2}\left(1 - \frac{1}{n^2\beta^2}\right) = \frac{2\pi z^2}{\lambda^2}\alpha \sin^2\Theta_C$$

$$\alpha = \frac{2\pi e^2}{hc}$$

Number of photons/L and radiation length depends on charge and velocity of particle

Using light detectors (photomultipliers) sensitive in 400-700 nm for an ideally 100% efficient detector in the visible

$$\frac{dN_\gamma}{dx} = \int_{\lambda_1}^{\lambda_2} d\lambda \frac{d^2N_\gamma}{dxd\lambda} = 2\pi z^2 \alpha \sin^2\Theta_C \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} = 2\pi z^2 \alpha \sin^2\Theta_C \left(\frac{1}{\lambda_1^2} - \frac{1}{\lambda_2^2}\right) = 490\ z^2 \sin\Theta_c \quad photons/cm$$

$$\frac{d^2N}{dxdE} = \frac{d^2N}{dxd\lambda}\frac{d\lambda}{dE} = \frac{\lambda^2}{2\pi\hbar c}\frac{d^2N}{dxd\lambda}$$

$$E = h\nu = \frac{hc}{\lambda} = \frac{2\pi\hbar c}{\lambda}$$

$$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$

$$\approx 370 \sin^2\theta_c(E)\ \mathrm{eV}^{-1}\mathrm{cm}^{-1} \qquad (z = 1)\ ,$$

Energy loss is about 10^4 less than 2 MeV/cm in water from ionization but directional effect

Example of radiators

Medium	n-1	γ_{th}	Photons/m
He (STP)	$3.5\ 10^{-5}$	120	3
CO_2 (STP)	$4.1\ 10^{-4}$	35	40
Silica aerogel	0.025-0.075	4.6-2.7	2400-6600
water	0.33	1.52	21300
Glass	0.46-0.75	1.37-1.22	26100-33100

PID: Cherenkov detectors

Threshold Cherenkov detectors (common particles can be distinguished up to ~30 GeV/c):

The Cherenkov threshold can be used to separate particles of momentum p and masses m_1 and $m_2 > m_1$. The radiator medium can be chosen such that the heavier particle is just below threshold: $\beta_2 \approx 1/n$

$$\sin^2\Theta_C = 1 - \frac{1}{\beta_1^2 n^2} \approx 1 - \frac{\beta_2^2}{\beta_1^2} \approx 1 - \frac{\beta_2^2}{\beta_1^2} = 1 - \frac{E_1^2}{E_2^2} \approx \frac{c^2(m_2^2 - m_1^2)}{p^2}$$

$$p >> m_2$$

Hence for a PMT with QE = 20%

$$N/L = 100\sin^2\Theta_C = 100\frac{c^2(m_2^2 - m_1^2)}{p^2}$$

And to detect 10 photoelectrons one needs a radiator of length

$$L = 10\frac{p^2}{c^2(m_2^2 - m_1^2)}$$ in cm

Eg for K/π separation at 1 GeV Npe/L ≈ 16/cm for π and by design 0 for K

PID: Cherenkov detectors

Differential or focusing Cherenkov detectors:

Angle of emission is measured with mirrors. There are 2 variations of the method:

1) If particles travel in the same direction the cone can be focused on to a slit diaphragm arranged to transmit light to a PMT. Scanning over a velocity range can be done adjusting the diaphragm to select different angles or modifying the refractive index by adjusting the pressure or composition of the gas

2) If particles do not travel along the same axis, the radiator can be contained between 2 spherical surfaces or radii R and 2R centered on the target or interaction region. The outer surface is lined with a mirror which focuses the Cherenkov radiation into a ring at the inner detector surface. The radius of the ring depends on q and hence on the particle velocity. An electronic image of the ring is constructed eg passing photons through a suitable gas, and drifting the liberated photoelectrons on the wires of a planar MWPC or drift chamber (ring image Cherenkov detector)