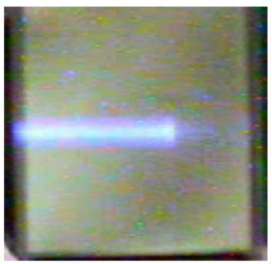
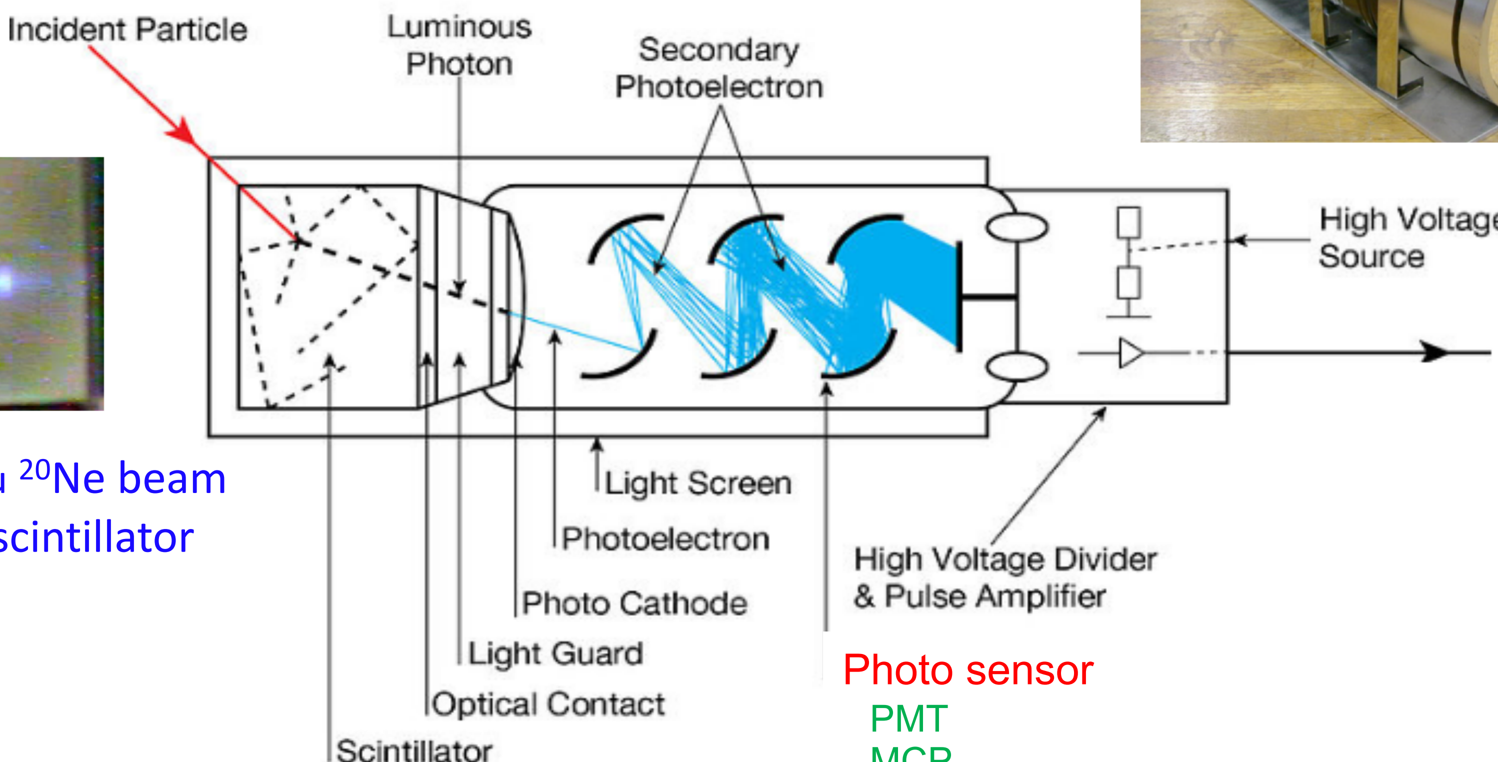
chap.5 Scintillaton Detectors

Basic Detector Setup

•Scintillation: Emission of photons following the excitation of atoms and molecules by radiation (γ or particle radiation).



300 MeV/u ^{20}Ne beam in a GSO scintillator



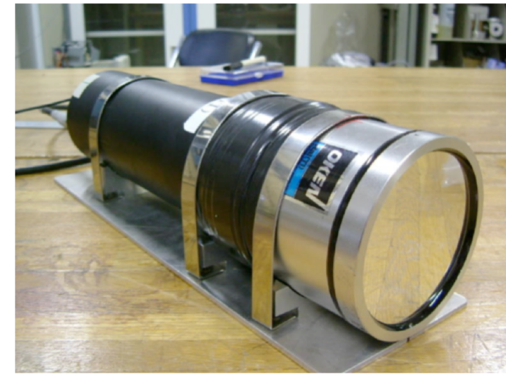


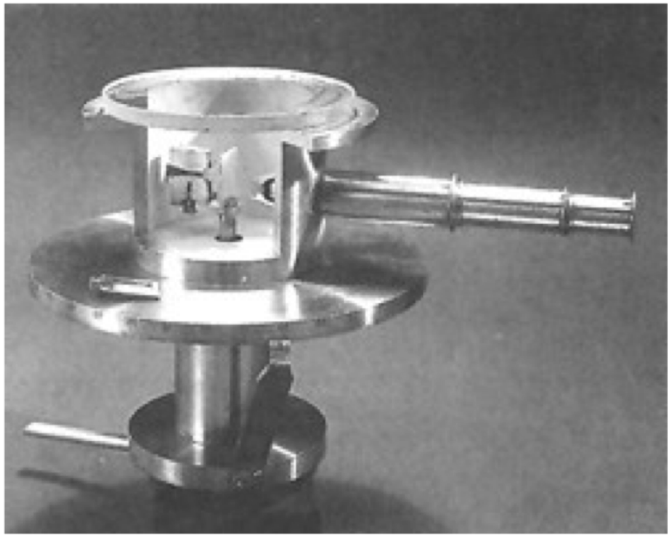
Photo sensor
PMT
MCP
SiPM

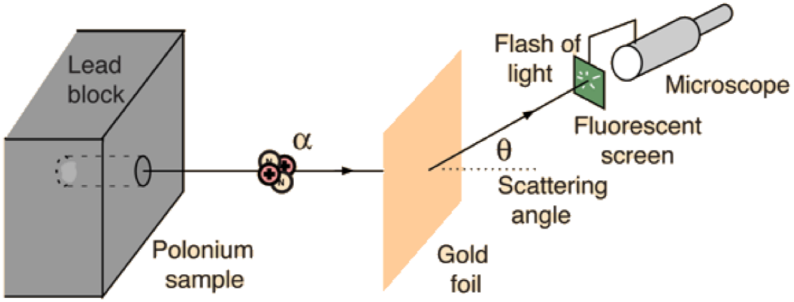
- Scintillator is coupled to a amplifying device such as a photomultiplier, the light is transformed into electrical pulses

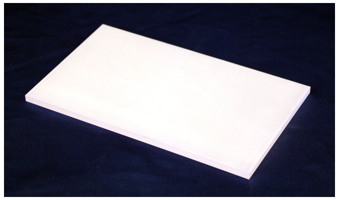
Early Scintillator counter

Rutherford's scattering experiment:

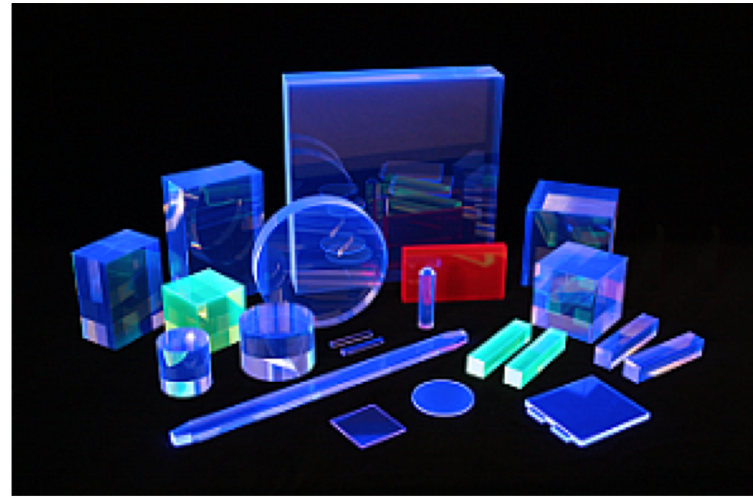
- Discovery of atomic nucleus with positive charge which holds most of its mass (1908-1913)
- Experiment:
  - Scattering of Alpha particles on thin metal (gold) foils)
  - Using microscope to count light flashes on ZnS (scintillation)







★ Scintillating materials:
- Inorganic crystals
- Organic crystals
- Organic liquids
- Plastic scintillators
- Nobel gases (gaseous and liquid)
- Scintillating glases

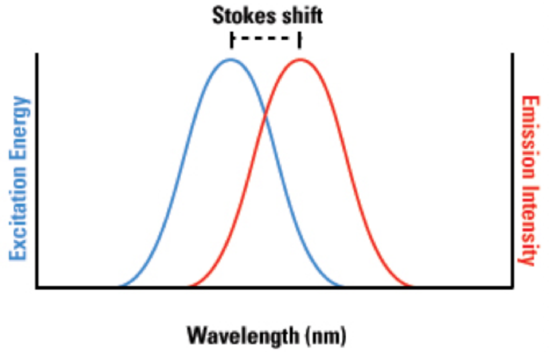


★ Advantages:
- Fast response time (especially organic scintillators, ~ ns)
- Sensitive to deposited energy
- Construction and operation simple ➔ cheap and reliable

★ Applications in nuclear- and particle physics:
- Trigger detectors for slow detectors (e.g. drift chambers)
- Time of flight counters (TOF-Counter)
- Calorimeters
- Position detectors (scintillating fibres)
- Detection and spectroscopy of thermal and fast neutrons
- Neutrino detectors (liquid scintillators)

Light output

- Only a few per cent of the deposited energy is transferred into light. The remaining energy is used up by ionisation, etc.
    - Emitted light usually of lower energy than deposited energy.
      → light shifted to longer wavelengths (Stokes shift)
    - In addition photons are lost in the scintillator itself (re-absorption) and in the light guide.



- Mean energy required to create a photon:
    - Anthracen ($C_{14}H_{10}$): ~ 60 eV
    - NaI:Tl:* ~ 25 eV
    - BGO ($Bi_4Ge_3O_{12}$): ~ 300 eV

* Sodiom iodide doped with Thallium

Luminescence

- Fluorescence(荧光):

  reemission occurs immediately after absorption, within 10 ns

- Phosphorescence/Afterglow(磷光):

  reemission is delayed, because the excited state is metastable

Equations describing the reemission process

1) Simple exponential decay:

$$N = \frac{N_0}{\tau_d}\exp(-\frac{t}{\tau_d})$$

Normalization factor

N: no. of photons emitted at a time t

N_0: total no. of photons emitted

τ_d: decay constant

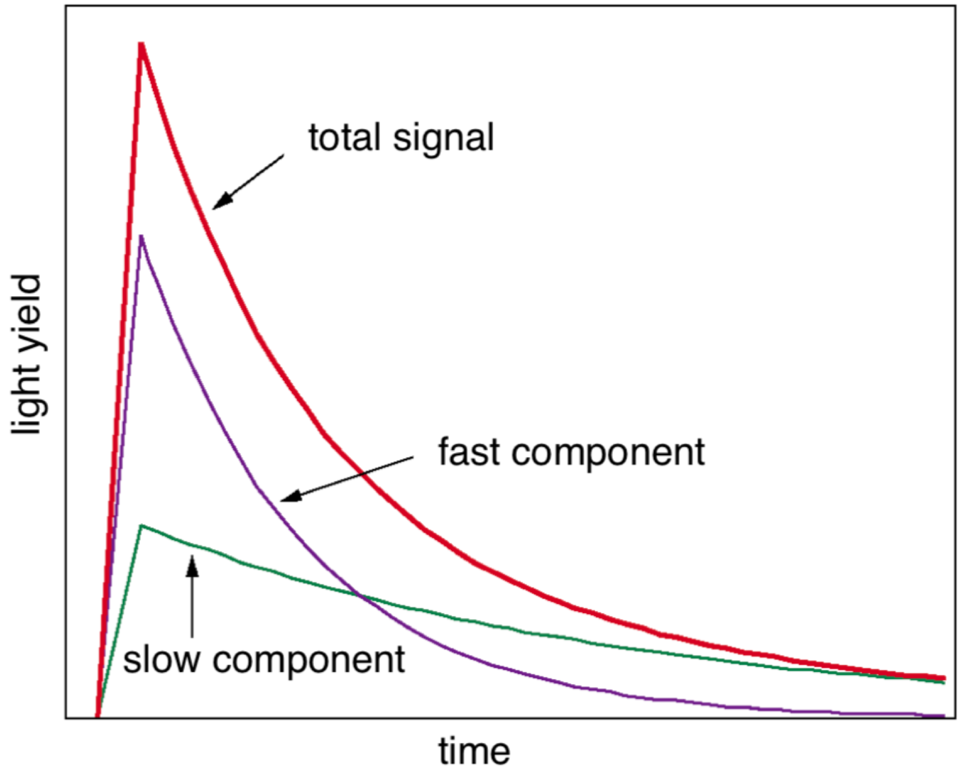
2) More complex decay, usually more accurate description:

$$N = A\exp(-\frac{t}{\tau_f}) + B\exp(-\frac{t}{\tau_s})$$

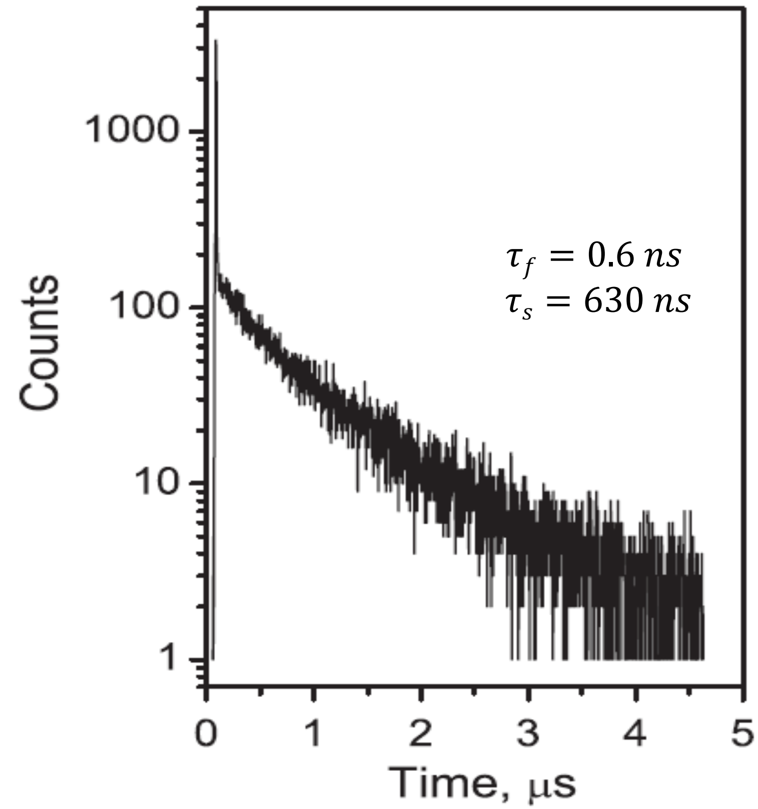
τ_f, τ_s : decay constant, f: fast, prompt s: slow, delayed

A, B: relative magnitudes

$\tau_r << \tau_d$ in most materials



Signal vs. time of a scintillator with fast and slow component.



Time decay curve of BaF_2

Pulse shape:

Requirements of detectors

Many materials show luminescence. However, a useful scintillation detector has to fulfil the following requirements:

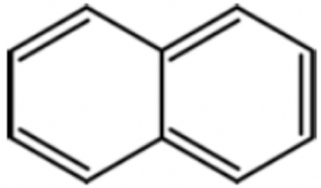
- High light yield Y_L, i.e. high efficiency to convert the excitation energy into fluorescence: $Y_L = \langle N_{photons} \rangle / E$
- Transparency with respect to the own fluorescence light. Otherwise the light is absorbed within the material itself.
- An emission spectra matched to the spectral sensitivity of the photo detector. Matching can also be achieved by introducing a wave length shifter.
- Refractive index of scintillator close to readout (glass in case of PMT)
- Short decay constant.

Organic scintillators

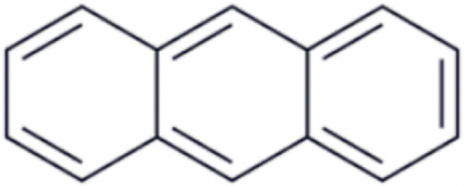
芳族烃
Aromatic hydrocarbon compounds:

e.g. Naphtalene [$C_{10}H_8$] 萘
Antracene [$C_{14}H_{10}$] 蒽
Stilbene [$C_{14}H_{12}$] 芪
…

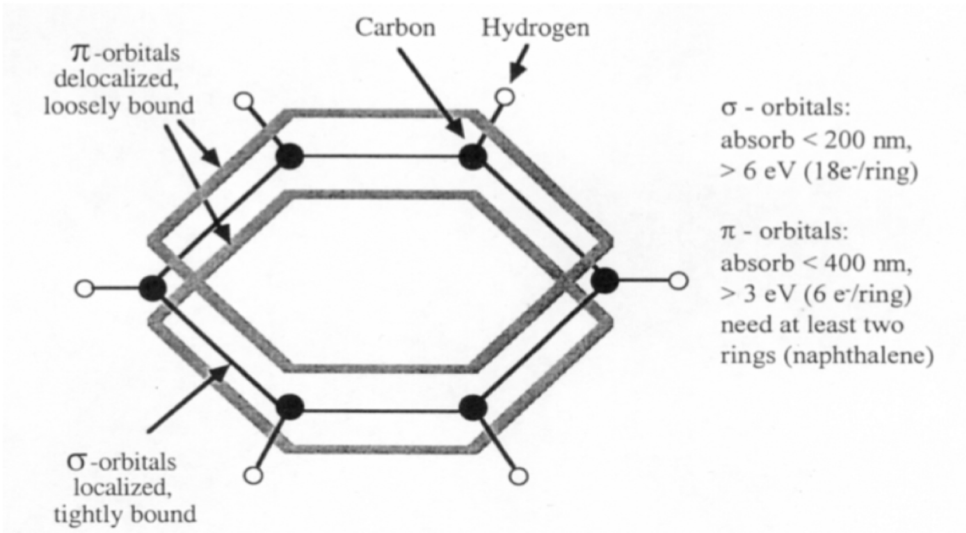
Naphtalene



Antracene

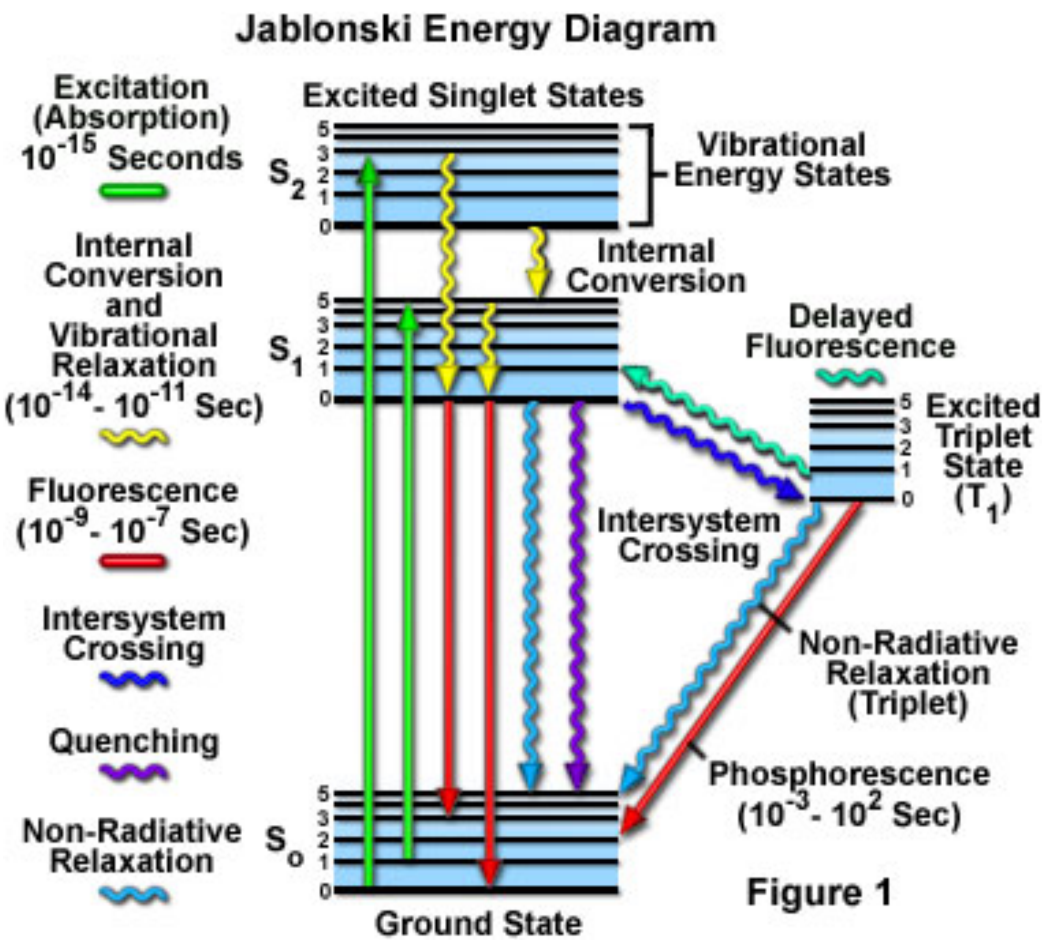


- contain aromatic molecules
  - i.e. they have a **benzene ring**
  - scintillation results from the physics of the benzene ring coupled to the molecule
- σ-bonds are in-plane with a bond angle of 120°, from sp2 hybridization
- π-orbitals are out-of-plane; the π-electrons overlap and are completely delocalized
- Scintillation light is produced from the de-excitation of the molecule



Scintillation mechanism in organic scintillators

π-Electronic States



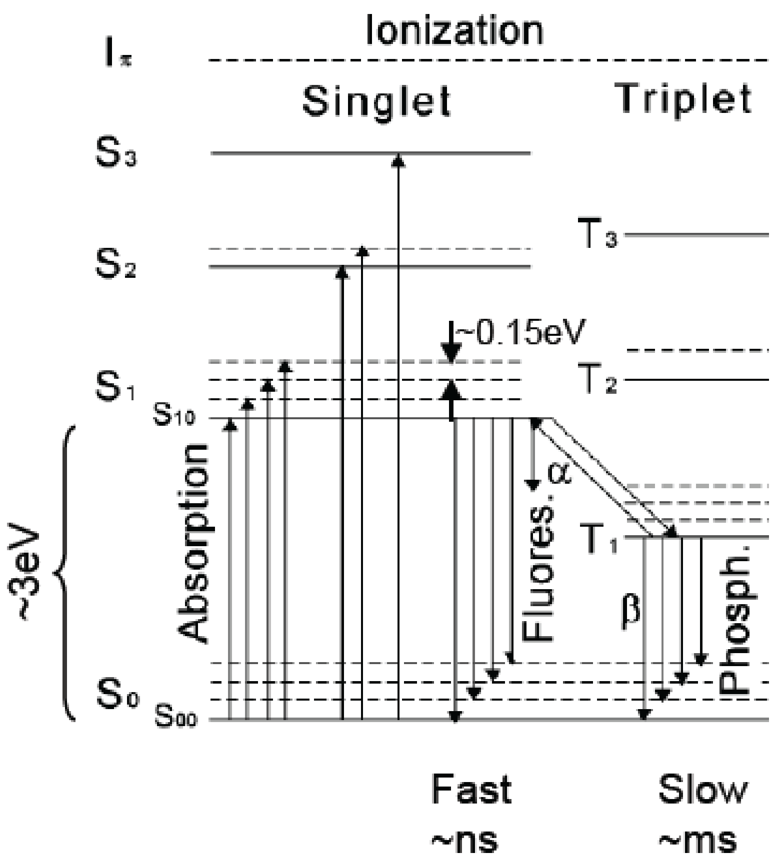
Decay from Singlet case

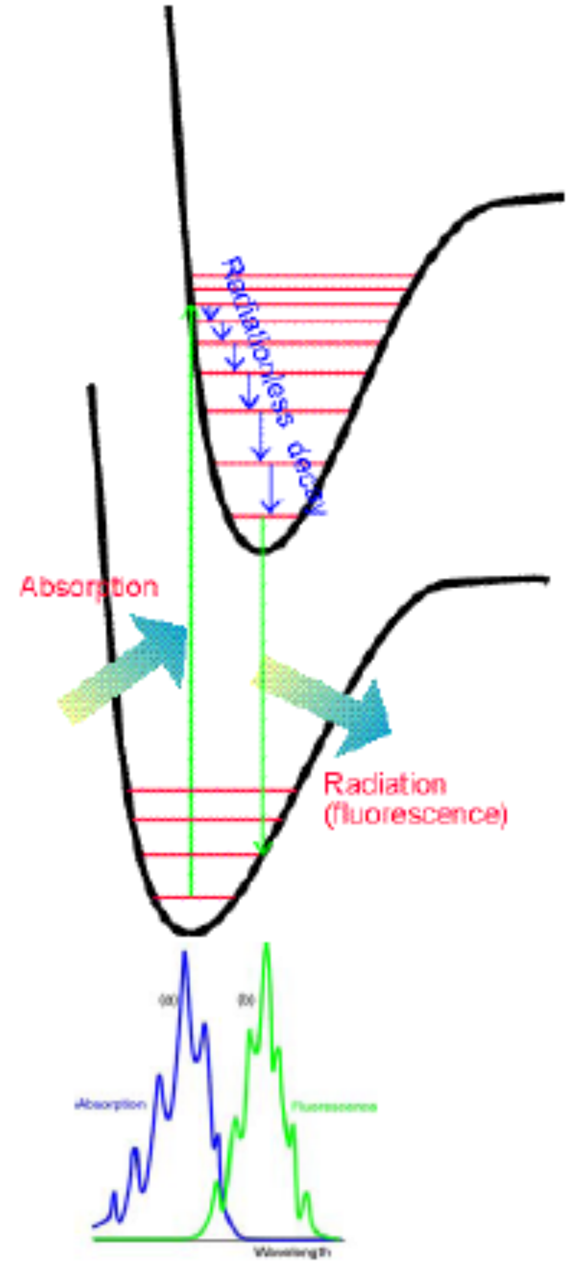
- **Internal degradation:** Singlet excitations decay immediately (≤10 ps) without emission of radiation ($S_2 \rightarrow S_1$, $S_3 \rightarrow S_2$…)
- **Fluorescence:** $S_1 \rightarrow S_0$ with radiation, to one of the vibrational states of the ground state S_0, ~few ns

Decay from triplet case

- Excited triplet state can't decay to ground state (angular momentum selection rules) results in delayed fluorescence and phosph

Note: The fact that S_1 decays to excited vibrational states of S_0 with emission of radiation energy less than required for the transition $S_0 \rightarrow S_1$ also explains the transparency of the scintillators to their own radiation.





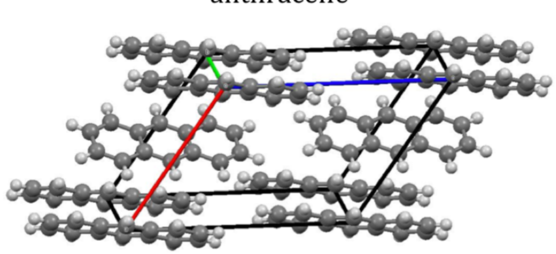
Pure organic crystals

- The particle ionization eventually excites molecular levels of the scintillating organic compound, which then rapidly de-excites (~*ns*) and emits UV photons
- Anthracene(30 ns); Trans-stilbene(few ns); Naphtalene(few ns)
- The absorption length of UV light in the most transparent organic material is very short (~1mm)
- Anthracene: highest light output
  light ouputs of scintillators are given as percent of anthracene output very often

Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, ns	Bulk Light Attenuation Length, cm	Refractive Index
BC-400	65	423	2.4	250	1.58
BC-404	68	408	1.8	160	1.58
BC-408	64	425	2.1	380	1.58
BC-412	60	434	3.3	400	1.58

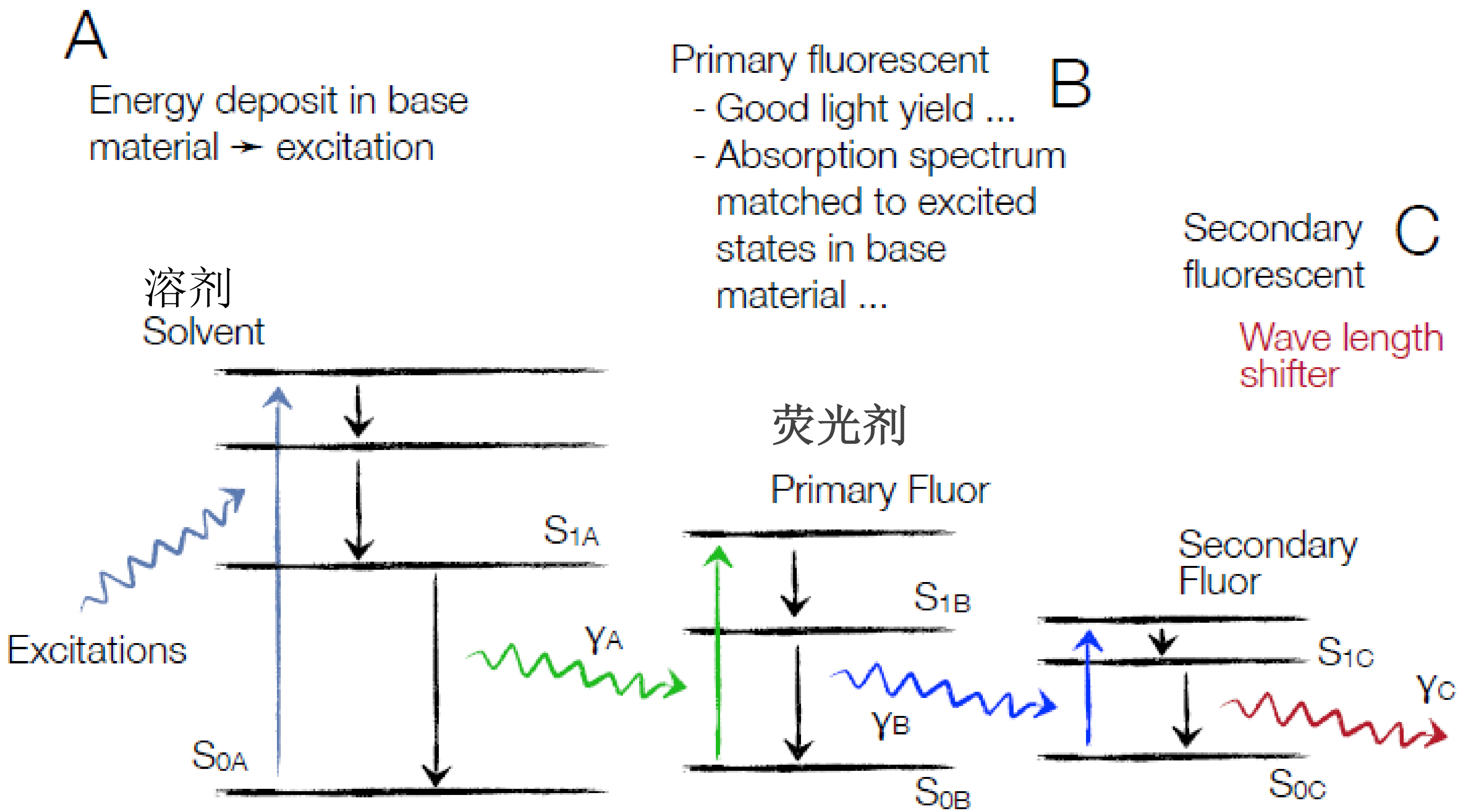
- channeling effect: for a constant source the response varies with the orientation of the crystal.

anthracene



Plastic and Liquid Scintillators

- Liquid solutions of one or more organic scintillators in an organic solvent



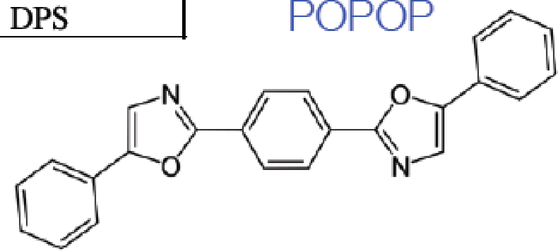
- The emission of the wavelength shifter material is obviously chosen to match the sensitivity of the PMT photo-cathode, typically a bluish visible light in the 400-500 nm range， longer wavelength photons with much longer absorption length

- Wave length shifter can be mixed into the scintillator or integrated into the light guide.

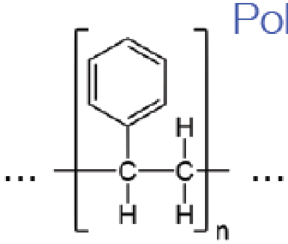
Some widely used solvents and solutes

	solvent	secondary fluor	tertiary fluor
Liquid scintillators	Benzene Toluene Xylene	p-terphenyl DPO PBD	POPOP BBO BPO
Plastic scintillators	Polyvinylbenzene Polyvinyltoluene Polystyrene (PVT)	p-terphenyl DPO PBD	POPOP TBP BBO DPS

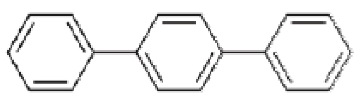
POPOP

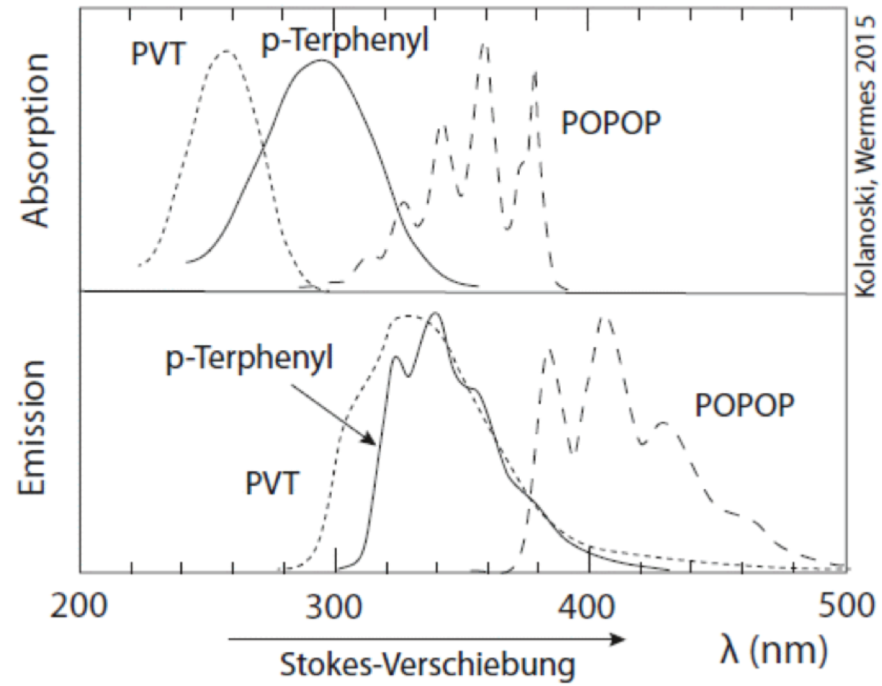


Polystyrene



p-Terphenyl





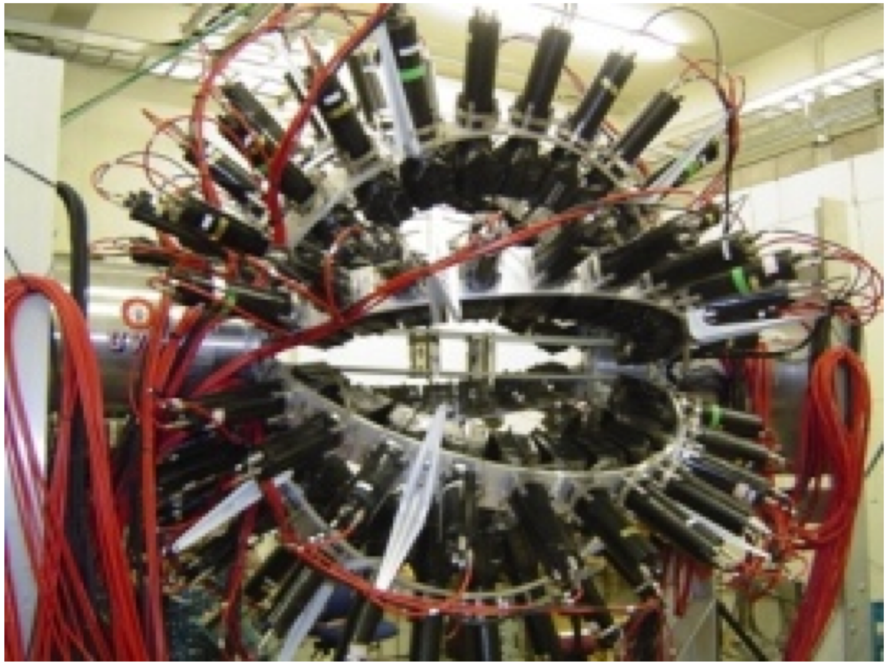
Liquid Scintillators

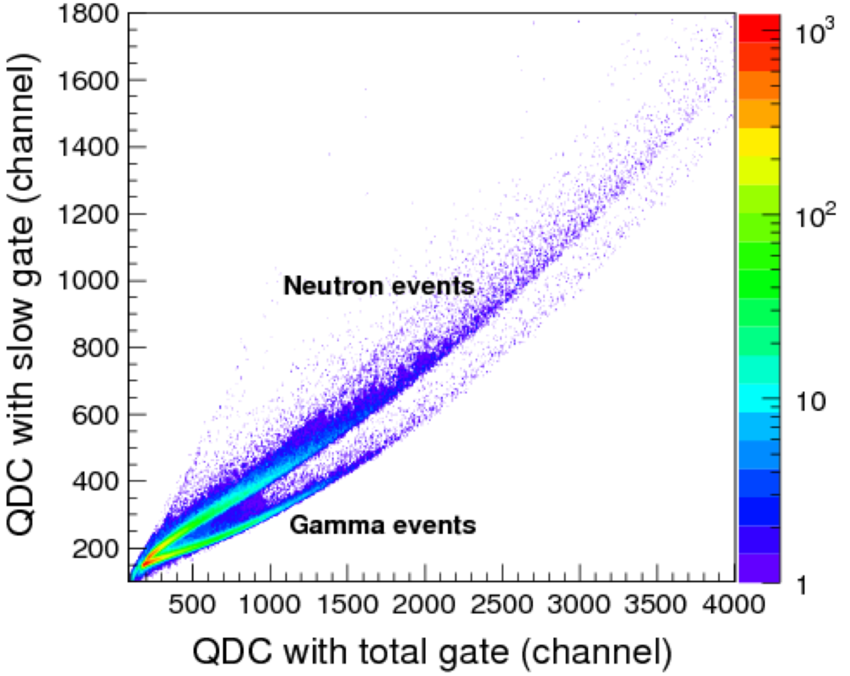
•Liquid solutions of one or more organic scintillators in an organic solvent

•Very fast and efficient, 3-4 ns, neutron TOF

•”loaded”: to increase efficiency (e.g. Boron-11, high neutron cross-section) or to shift wavelength

•Pulse shape discrimination





Plastics

- Solution of organic scintillator in solid plastic solvent
- Density 1.03~1.20g/cm^3
- Yield ~ 1 detectable photon / 200eV deposit
- Decay time ~ a few nsec, Rise time is less than 1nsec.

→ Combined with fast detector, sub-ns timing resolution is possible.

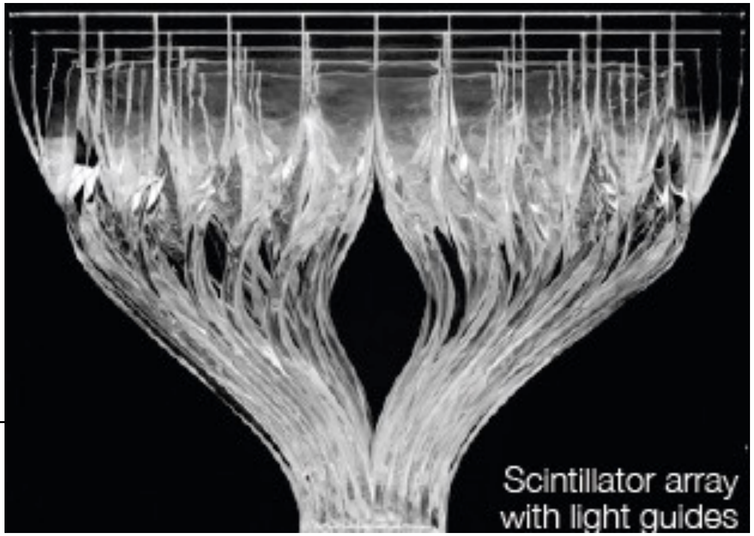
- Rise time cannot be ignored in the discription of the light pulse
- Hydrogen content is high → Sensitive to proton recoils from fast neutrons.
- low Z → relatively low sensitivity to photons

$$N(t) = N_0 f(\sigma, t) \exp(-\frac{t}{\tau})$$

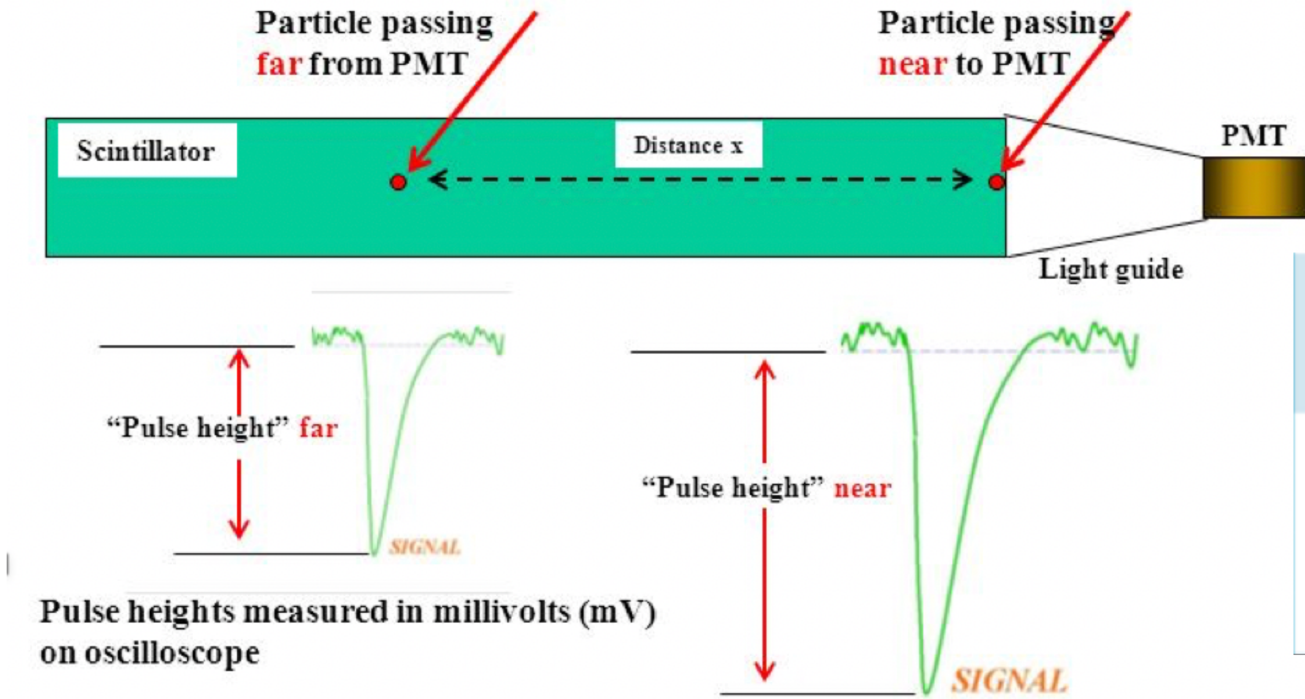
$f(\sigma, t)$ ↑ gaussian

Derived from fits →

Scintillator	σ [ns]	τ [ns]
NE102A	0.7	2.4
NE111	0.2	1.7
Naton 136	0.5	1.87


Scintillator array with light guides

- Plastic scintillator are available commercially with a good selection of standard sizes of rods, cylinders and flat sheets.
- Plastics are often the only practical choice if large-volume solid scintillator are needed. In these cases the self-absorption of scintillator light no longer be negligible: λ: attenuation lenght



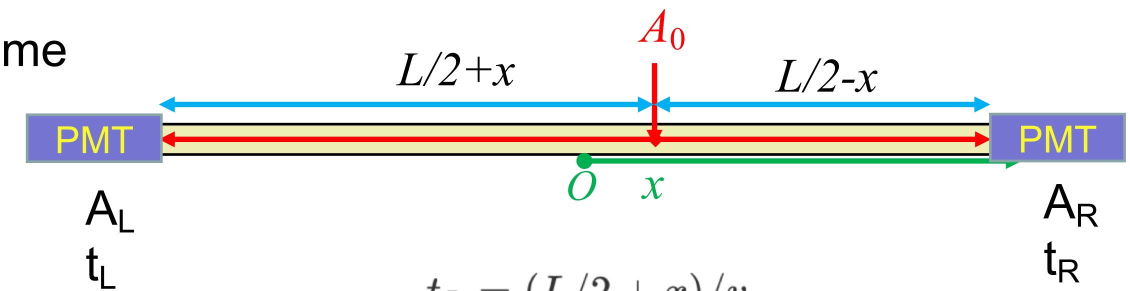
Scintillator	Bulk Light Attenuation Length, cm
BC-400	250
BC-404	160
BC-408	380
BC-412	400

Typically, the pulse height as a function of distance x away from the near end of the scintillator is described by the function

$$\text{Pulse Height}(x) = \text{Pulse Height}(x = 0) \times e^{-x/\lambda}$$

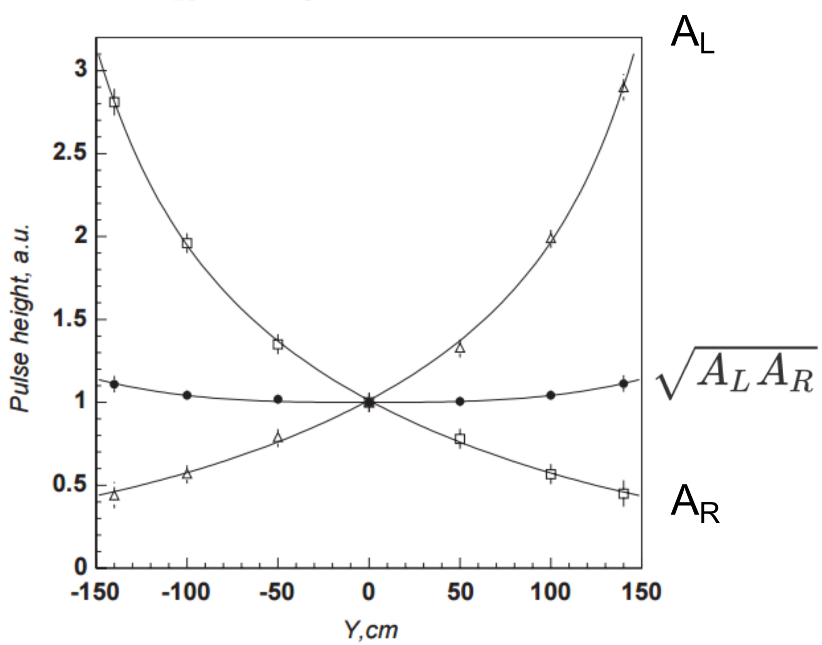
Long Scintillation Counter

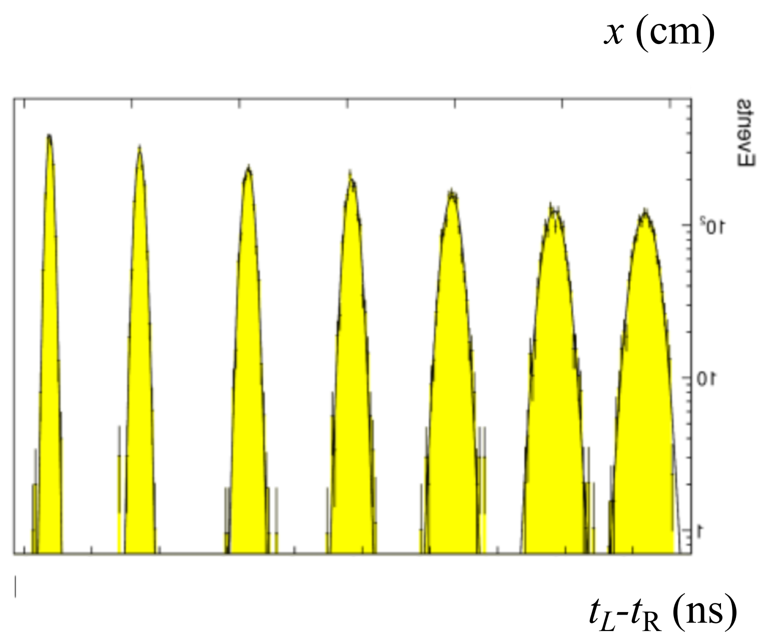
- Read out on both ends: A and time
- Attenuation length: λ
- Light speed in scin.: v_{sc}



$$A_L = A_0 e^{-(L/2+x)/\lambda}$$
$$A_R = A_0 e^{-(L/2-x)/\lambda}$$

$$t_L = (L/2 + x)/v_{sc}$$
$$t_R = (L/2 - x)/v_{sc}$$





$$A_L A_R = A_0^2 e^{-L/\lambda}$$
$$A_0 \propto \sqrt{A_L A_R}$$

$$x = \frac{v_{sc}}{2}(t_L - t_R)$$

Particle identification using hodoscope

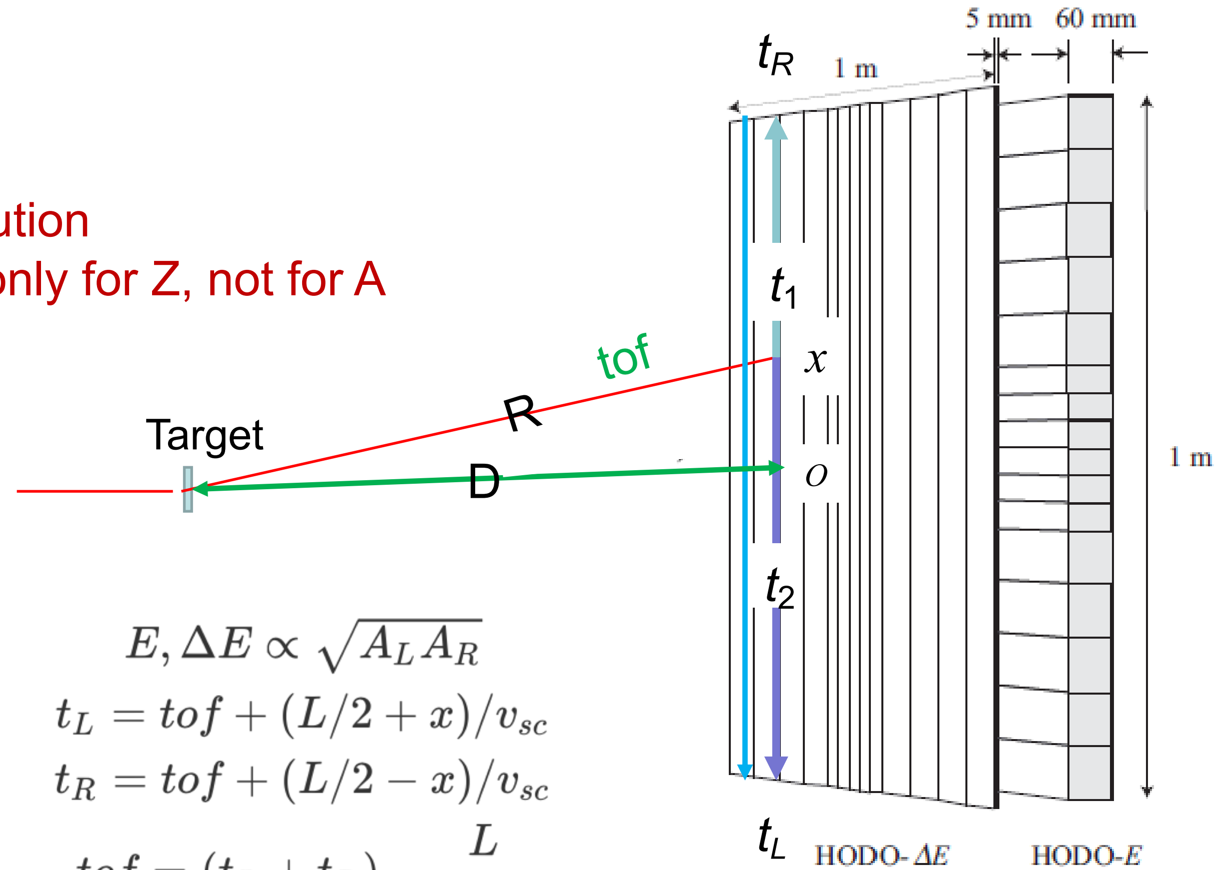
Plastic detectors:

✓ Good timing

✓ Large acceptance

x Poor energy resolution

- PID with ΔE-E: only for Z, not for A



$$\Delta E \propto \frac{z^2}{v^2}$$

$$E \propto A v^2$$

$$tof = \frac{\sqrt{D^2 + x^2}}{v}$$

$$TOF = tof/\sqrt{D^2 + x^2} \propto 1/v$$

$$E, \Delta E \propto \sqrt{A_L A_R}$$

$$t_L = tof + (L/2 + x)/v_{sc}$$

$$t_R = tof + (L/2 - x)/v_{sc}$$

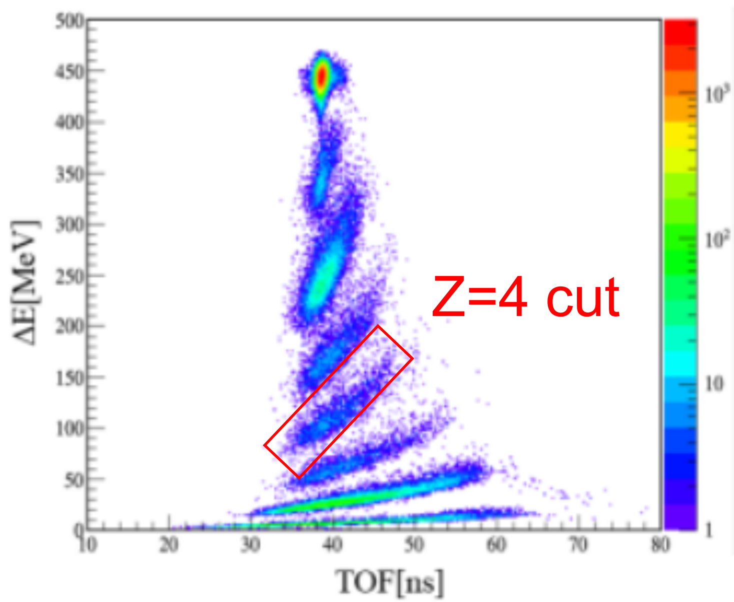
$$tof = (t_L + t_R) - \frac{L}{2v_{sc}}$$

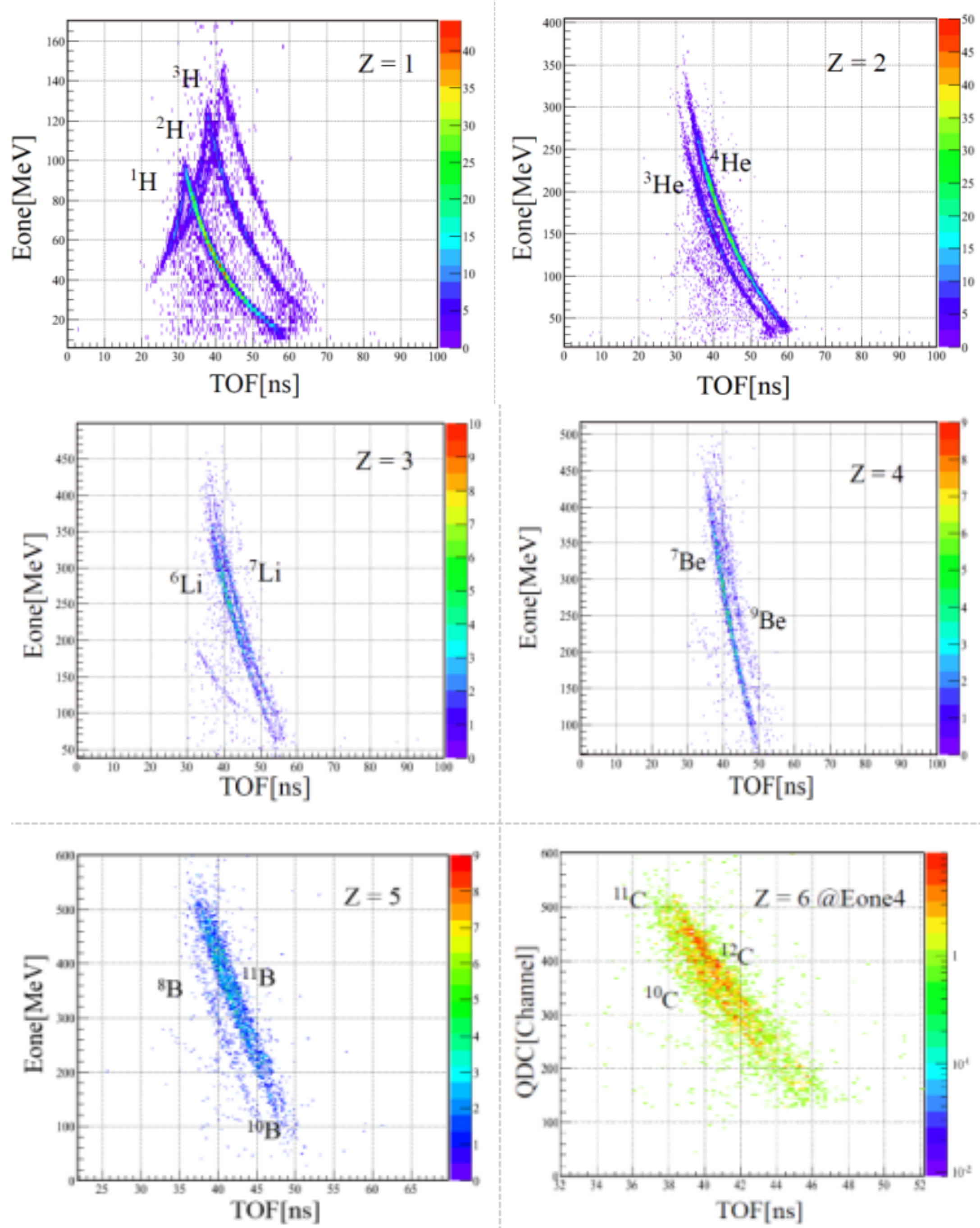
$$\Delta E \propto z^2 \cdot TOF^2$$

$$E \propto A \, / \, TOF^2$$

$$\Delta E \propto z^2 \cdot TOF^2$$

$$E \propto A / TOF^2$$





Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, ns	Bulk Light Attenuation Length, cm	Refractive Index
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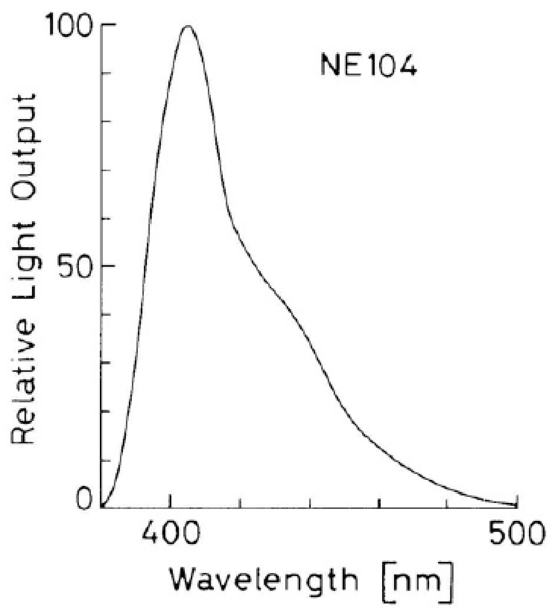
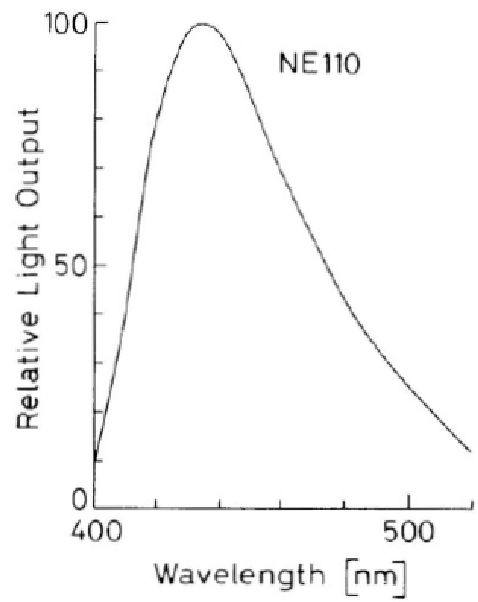




- Cautions
  - Aging : diminishes the light yield
    - Avoid solvent vapors, high temperatures, mechanical flexing
  - Surface crazing : microcracks destroy the capability of the total reflection
    - Avoid oils, solvents, fingerprints.
  - Afterglow
    - Plastic scintillators have small (10^{-4}) but finite long-lived (~several hundreds nsec) luminescence which does not follow simple exponential decay.
  - Radiation damage
    - Not well documented and well understood. Calibration is necessary when used under high dose.

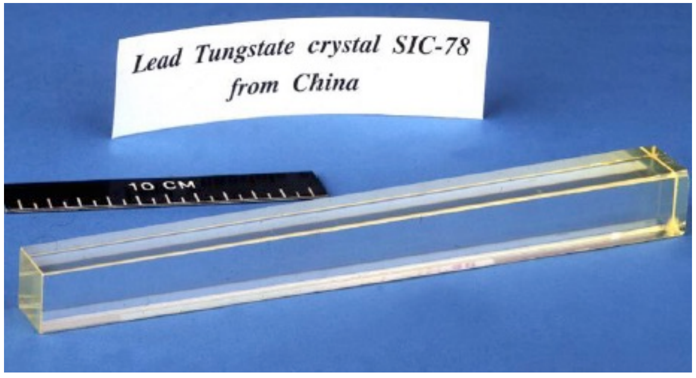
Inorganic scintillators

Materials:

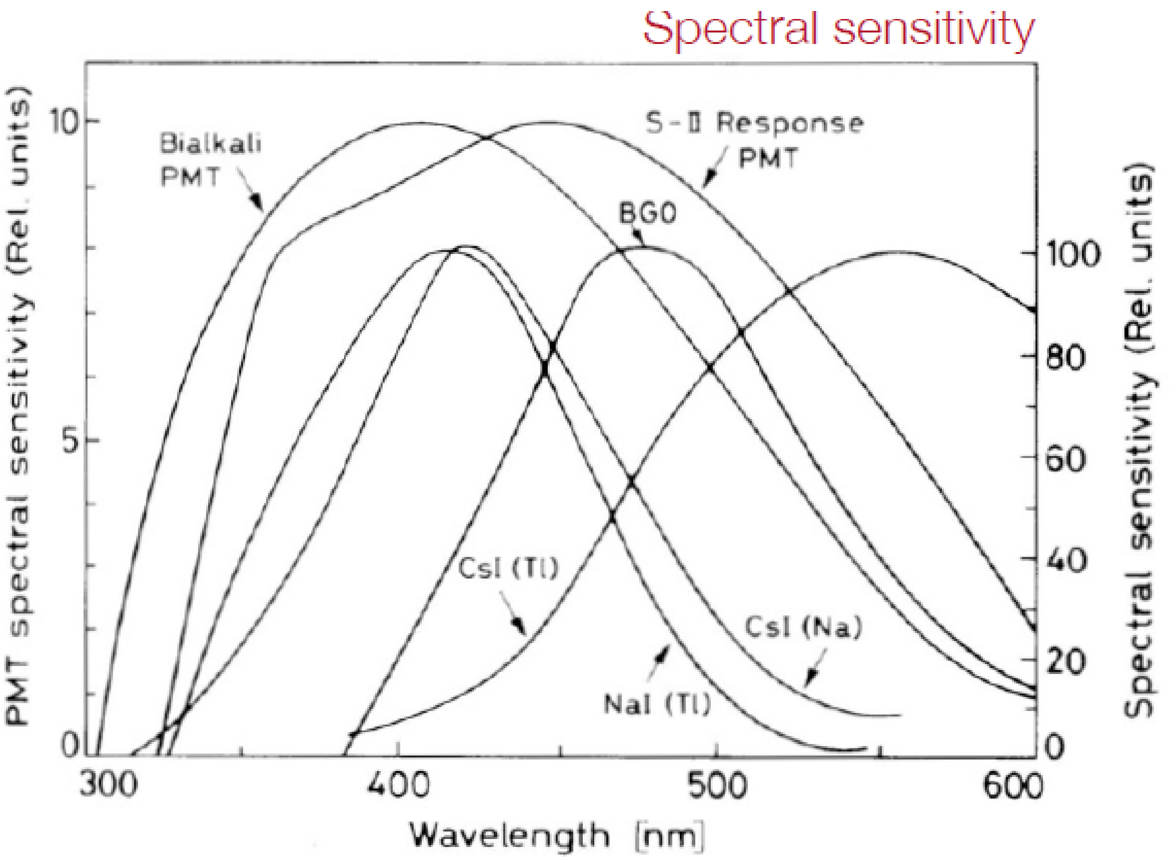
Sodium iodide (NaI)
Cesium iodide (CsI)
Barium fluoride (BaF_2)

NaI

$PbWO_4$



Light Output & PMT Sensitivity

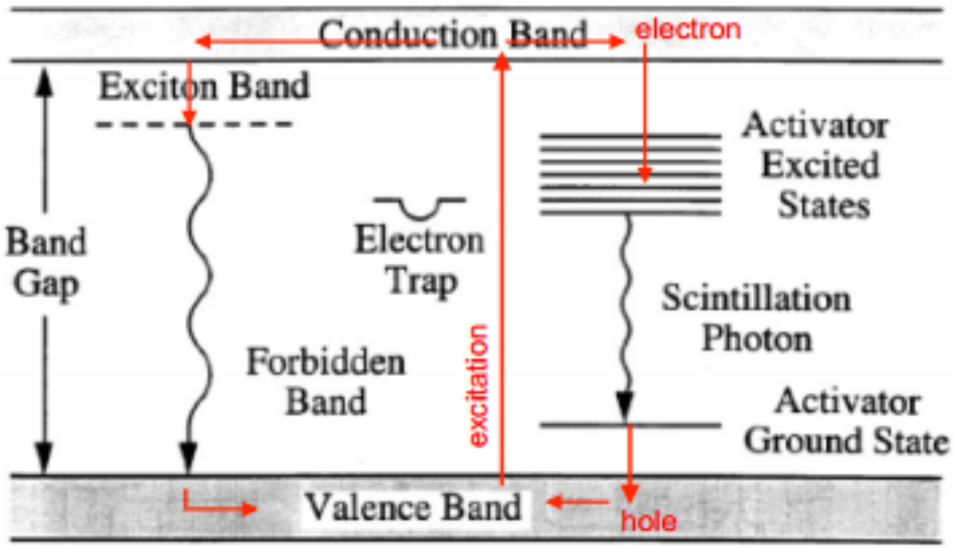


When paritcle inter the crystal, radiation creates electron-hole pairs

two processes:

Ionization: free electrons in conduction band and free holes in valance band

Excitons: electron in the exciton band, electron and hole are still bound, pair can move freely



Pure inorganic scintillators(NaI)

- electron-hole recombination via photon emission

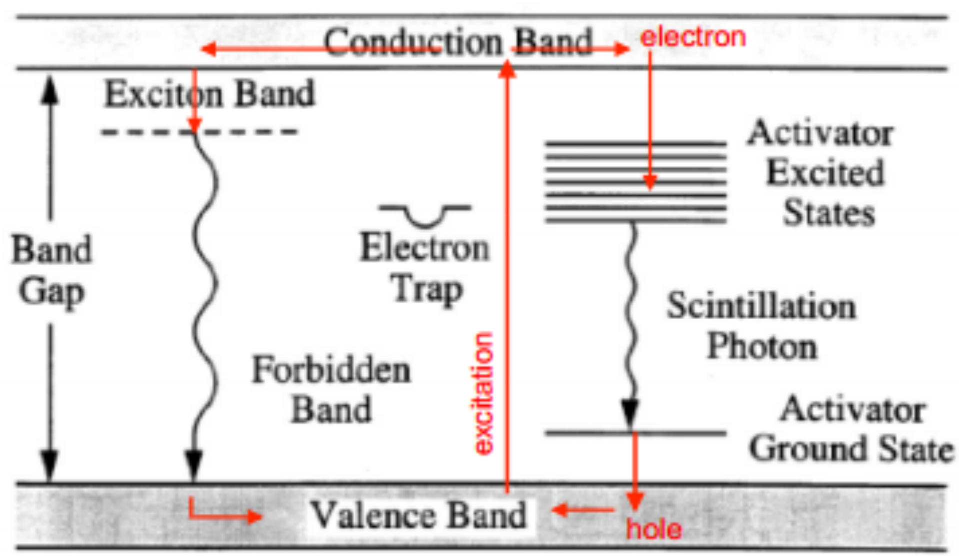
– inefficient

– photon energy > visible light

– emission wavelength = absorption wavelength -> self-absorption

Impurity Atoms: **Tl in NaI-> NaI(Tl)**

- electron levels in the forbidden energy gap can be locally created
- migrating free holes or a hole from an exciton pair encountering an impurity center can then ionize the impurity atom
- subsequent electron arrives and can fall into the opening left by the hole and make a transition from an excited state to the ground state emitting radiation if such a deexcitationis allowed



- for doped crystals: the decay time primarily depends on the lifetime of the activator excited state
- examples of doped crystals: NaI(Tl), CsI(Tl), CaF_2(Eu)

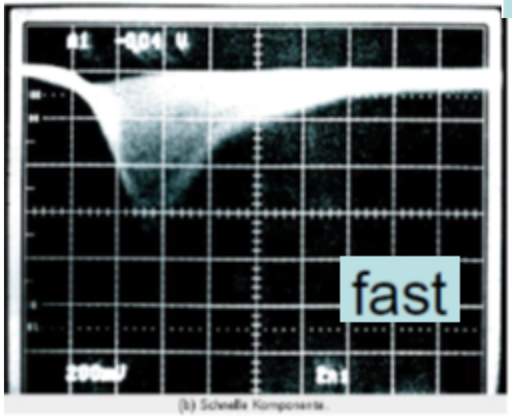
Types of inorganic scintillators

- unactivated fast
- unactivated slow
- Tl-activated
- Ce-activated
- glass

Unactivated fast inorganic scintillators

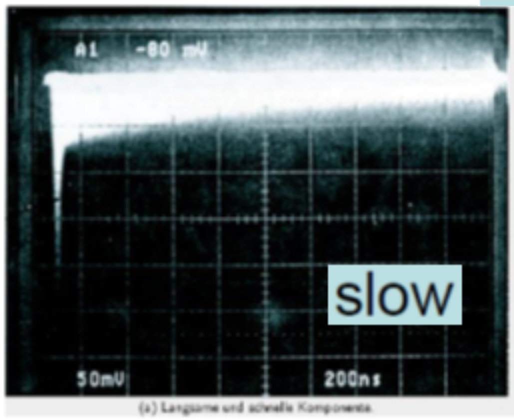
- fast component with low light yield
- BaF_2
  - only high-Z scintillator with decay time < 1 ns
    τ = 0.6 ns at λ ~ 220 nm, 15% of light yield
  - slow component
    τ = 630 ns at λ ~ 220 nm, 85% of light yield
- CsI
  - fast component τ ~ 10 ns
  - slow component τ up to several μs
    - related to impurities

BaF_2



2ns/square

BaF_2



200ns/square

Unactivated slow inorganic scintillators

- BGO (bismuth germanate, $Bi_4Ge_3O_{16}$)

  Form an *exciton* (bound yet mobile e/hole pair) that decays directly

  – very high Z

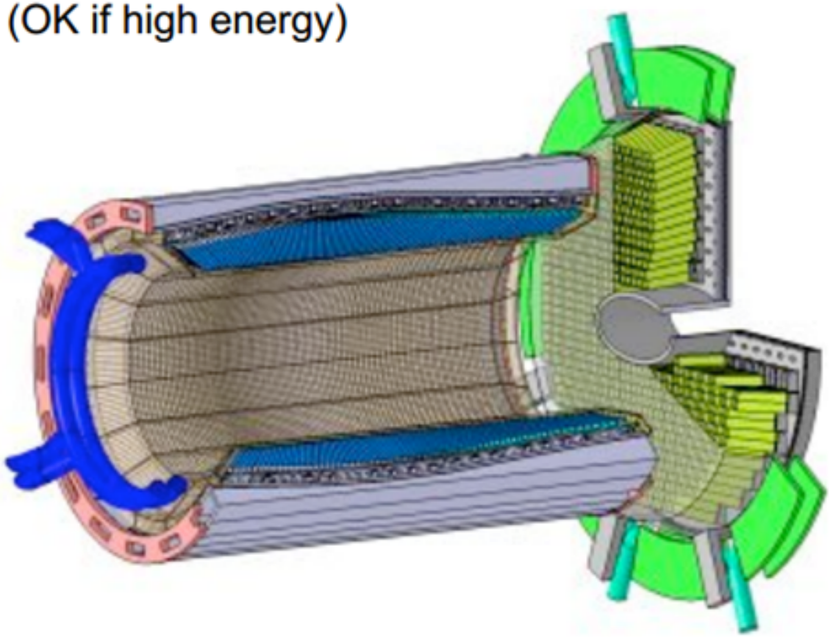
- $CdWO_4$ (cadmium tungstate)
- $PbWO_4$ (lead tungstate) Self-Activated
  - chemically pure crystal has luminscence centres (probably interstitial) due to stoichiometric excess of one of the constituents

  – very high Z

  – very poor light yield (OK if high energy)

- detector PANDA experiment
- electromagnetic calorimeter
- 15 552 $PbWO_4$ crystals

  www-panda.gsi.de



Tl-activated inorganic scintillators

- slow and bright
- NaI(Tl)
  - most widely used scintillator
  - high light yield (38 000 photons/MeV)
  - τ = 230 ns
- CsI(Tl)
  - 65 000 photons/MeV
  - τ = 0.68 (64%), 3.34 (36%) μs

Ce-activated inorganic scintillators

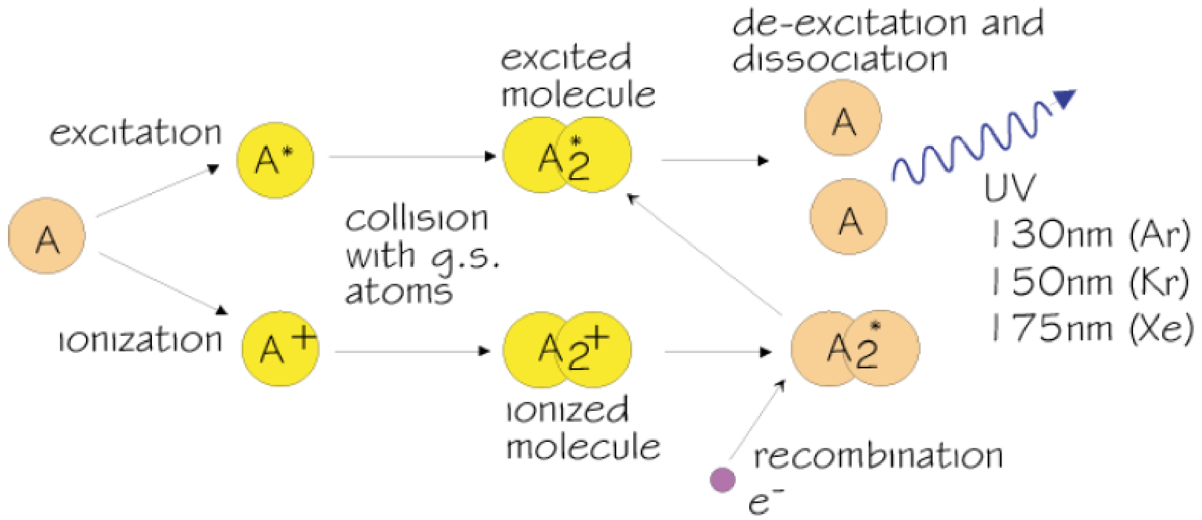
- relatively fast (τ ~ 20-80 ns) and bright
- examples:
  - GSO(Ce) (gadolinium silicate, Gd_2SiO_5)
  - LSO(Ce) (lutetium oxyorthosilicate, Lu_2SiO_5)
  - $LaCl_3$(Ce), $LaBr_3$(Ce)

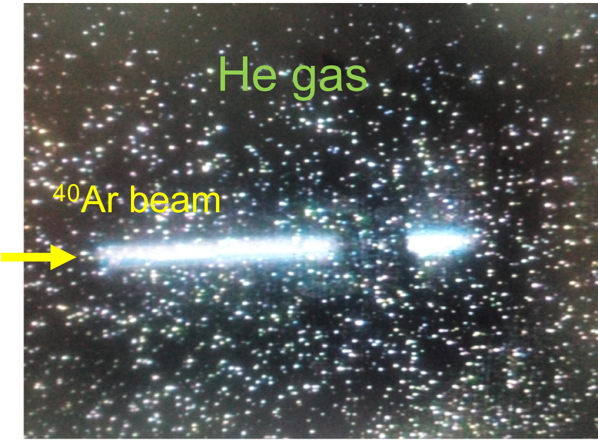
Glass scintillators

- containing Li or B and activated with Ce
- for neutron detection
  - enriched to ~95% ^{6}Li:
    - $^{6}Li(n,\alpha)^{3}H$ with α, ^{3}H being detected
    - Q = 4.78 MeV → detected energy = neutron energy + 4.78 MeV

- Boron glasses 10 times lower light ouputs than lithium
- Glass detectors usually used for neutron detection, also sensitive to beta and gamma radiation
- Resistant to all organic and inorganic reagents (exception hydrofluonic acid)
- High melting points, useful in extreme environmental conditions
- Response time: between plastics and inorganic crystals, few 10th of ns
- Low light output: < 20-30% of anthracene

Gaseous Detectors / Liquid Scintillator





- Noble gases: xenon, krypton, argon, and helium + nitrogen
- Atoms individually excited
- Decay time: 1 ns
- UV light
- Used in experiments with heavy charged particles or fission fragments
- High light yield: e.g. 40,000 photons/MeV for argon

• Liquid noble gas scintillators used in experiments searching for dark matter: e.g. XENON100 at LNGS, Italy, 161 kg LXe, 242 PMTs.

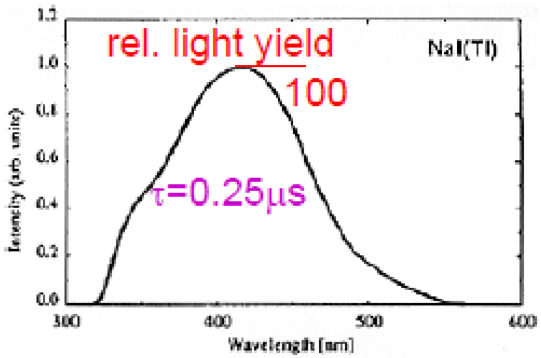


Figure 1. Scintillation emission spectrum of a canned NaI(Tl) crystal.

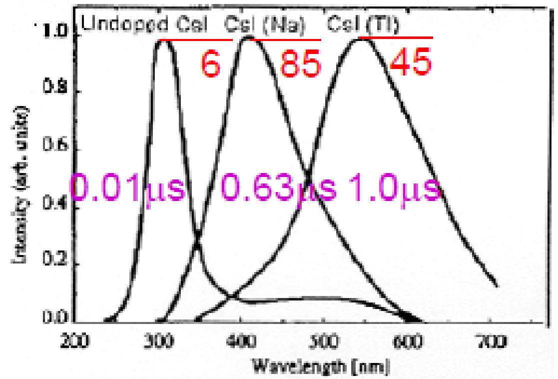


Figure 1. Scintillation emission spectrum of undoped CsI, CsI(Na) and CsI(Tl).

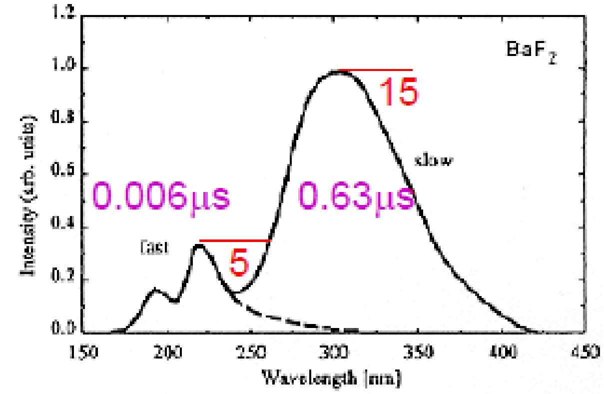


Fig. 1. Scintillation emission spectrum of BaF_2.

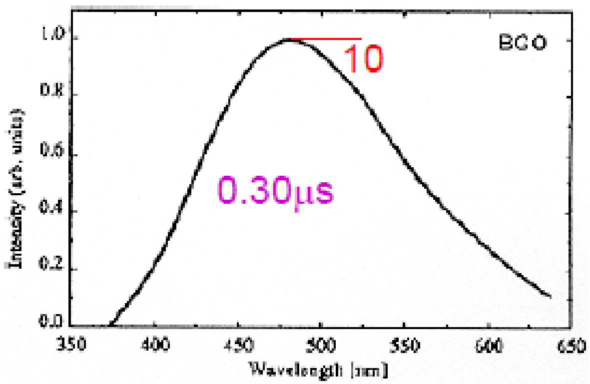
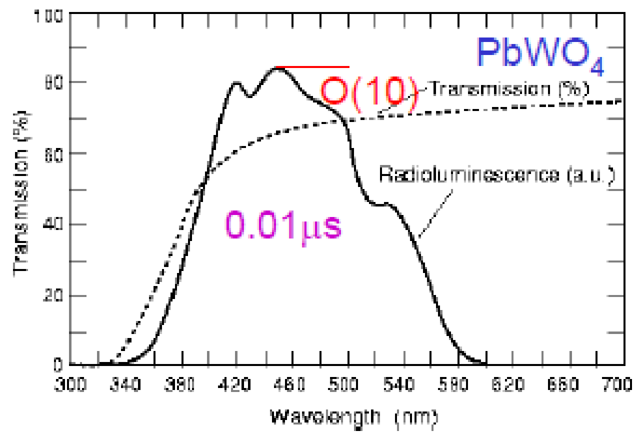


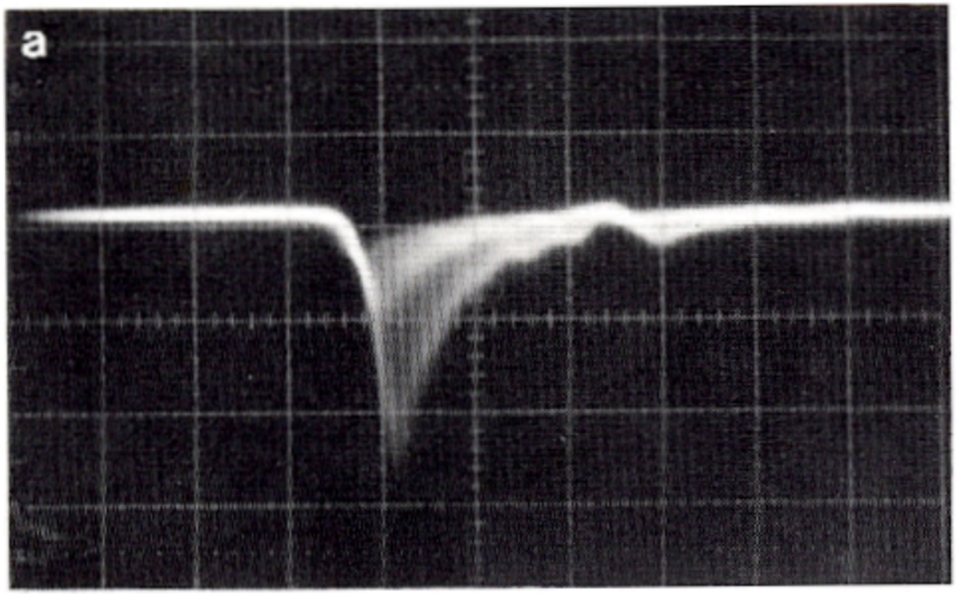
Fig. 1. Scintillation emission spectrum of BGO.



Scintillator composition	Density (g/cm^3)	Index of refraction	Wavelength of max.Em. (nm)	Decay time Constant (μs)	Scinti Pulse height[1)]	Notes
NaI(Tl)	3.67	1.9	410	0.25	100	2)
CsI	4.51	1.8	310	0.01	6	3)
CsI(Tl)	4.51	1.8	565	1.0	45	3)
CaF_2(Eu)	3.19	1.4	435	0.9	50	
BaF_2	4.88	1.5	190/220 310	0,0006 0.63	5 15	
BGO	7.13	2.2	480	0.30	10	
$CdW0_4$	7.90	2.3	540	5.0	40	
$PbWO_4$	8.28	2.1	440	0.020	0.1	
CeF_3	6.16	1.7	300 340	0.005 0.020	5	
GSO	6.71	1.9	430	0.060	40	
LSO	7	1.8	420	0.040	75	
YAP	5.50	1.9	370	0.030	70	

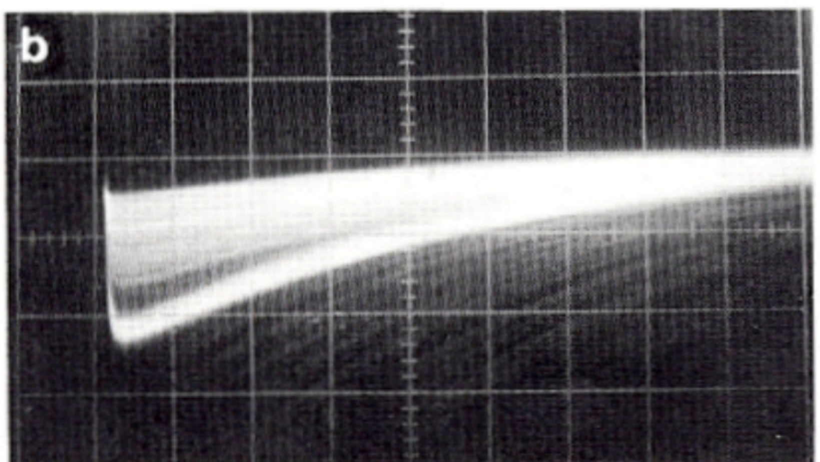
1) Relative to NaI(Tl) in %; 2) Hygroscopic; 3) Water soluble

Oscilloscope traces from scintillation counters



Plastic scintillator

10 nsec / division



Inorganic crystal, NaI

5000 nsec / division
(Longer time scale for fluorescence to occur)

Light output response

For an ideal scintillator and low ionization density

Luminescence ∝ Energy dissipated in scintillator

$$L = AE \rightarrow \frac{dL}{dx} = A\frac{dE}{dx}$$

The dependence of light output from energy deposition is usually not linear in organic scintillators.

A high density of excited molecules along the particle track causes de-excitation without photon emission (quenching effect).

→ Light output becomes saturated

Light output described by Birks law:

$$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + K_B\frac{dE}{dx}}$$

dL/dx … Light output per path length

dE/dx … Energy loss per path length

A …… scintillation efficiency

K_B …… Birks constant

K_B needs to be determined experimentally. Typical numbers 10^{-2} g/(cm^2 MeV)

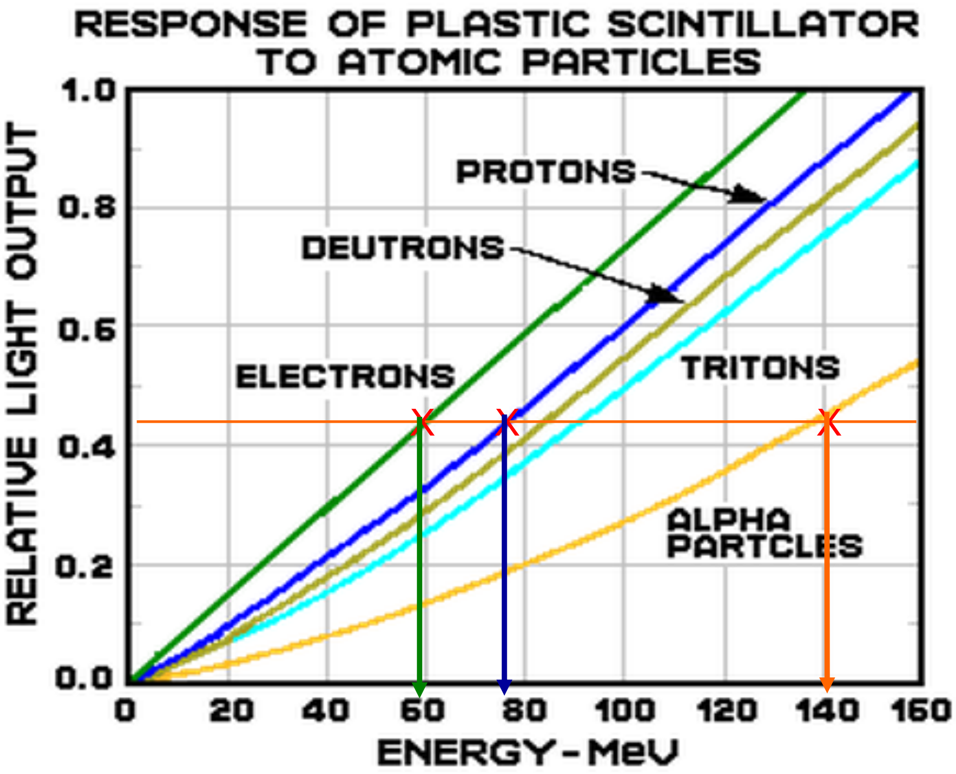
The response of organic scintillators to electrons is known to be a linear function of the deposited energy for electron energies above approximately 100 keV.

$E_{electron}$=60MeV

E_{proton}=78MeV

E_{alpha}=140MeV

Same light output



The scintillation pulse-height is commonly measured in electron equivalent energy units E_{ee}=60MeV

Energy calibration of the organic scintillator

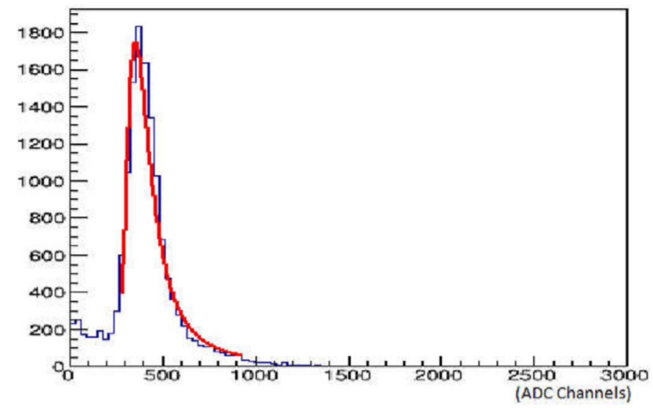
The Compton edge can be used for the energy calibration of the detector, and further, comparison of the light output from different detector materials.

Calculated values of Compton edges of backscattered gammas.

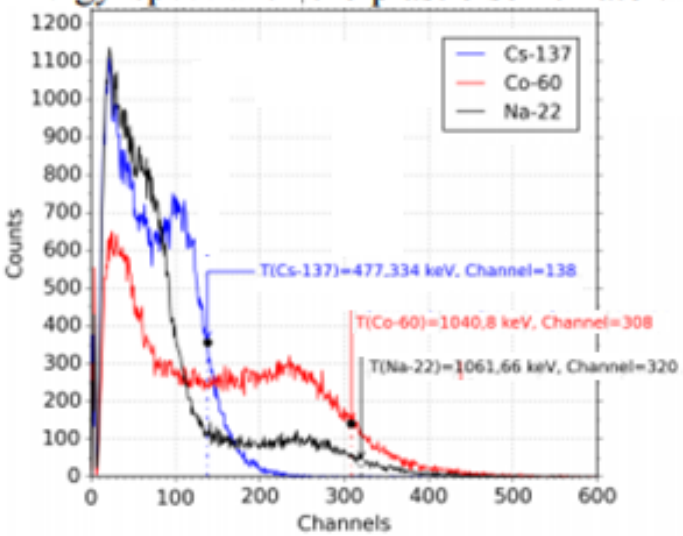
Source	Gamma Energy, keV	Compton Energy, keV
Na-22	1274,5	1061,67
Co-60	1173,228 1332,492	Aver. 1040,79
Cs-137	661,657	477,334

- **4.4 MeV γ from Am/Be neutron source**

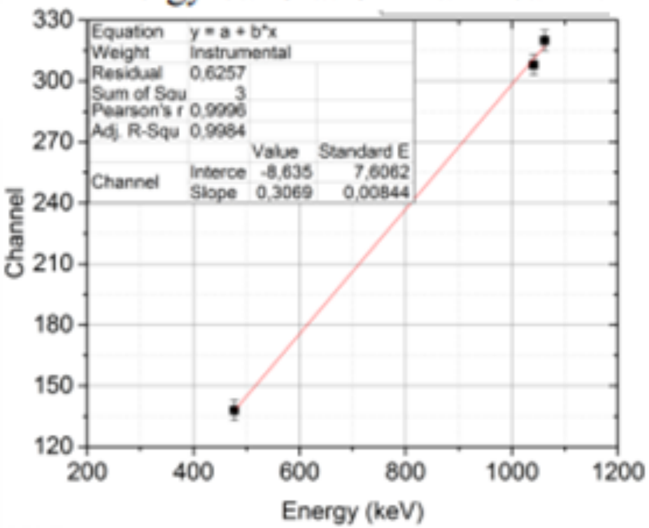
- **Cosmic rays, 2MeVee per cm for plastic**



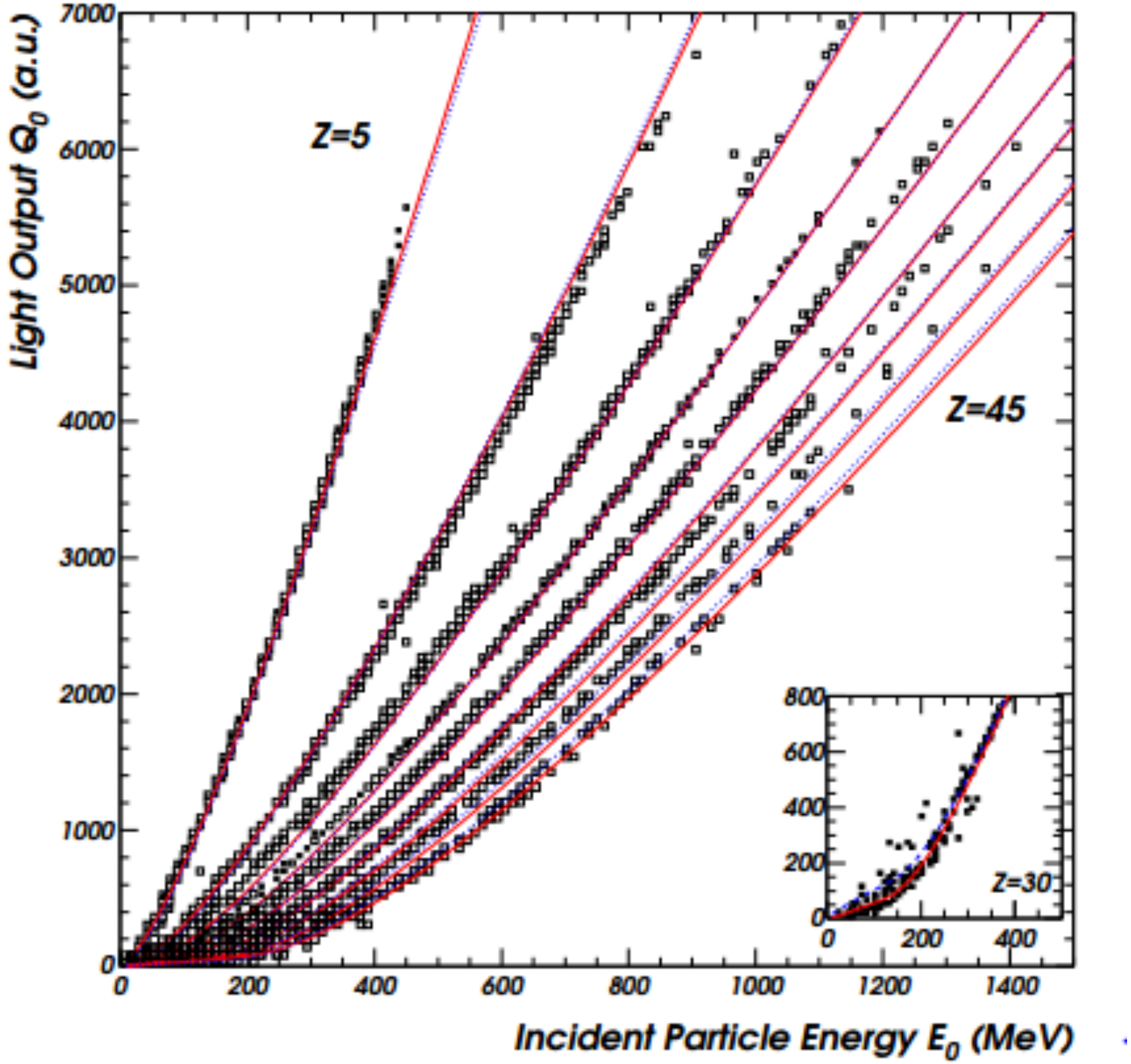
Energy spectra of the plastic scintillator.



Energy calibration via linear fit



Response of CsI(Tl) scintillators



Pulse shape discrimination

Example: organic scintillator

High dE/dx→ high density of excited molecules

- high ionization density can quench the excited singlet π-electrons
  - the fast component is thus reduced for high dE/dx particles

→ fast component reduced relative to slow component

•Characteristic for particle type/exciting radiation

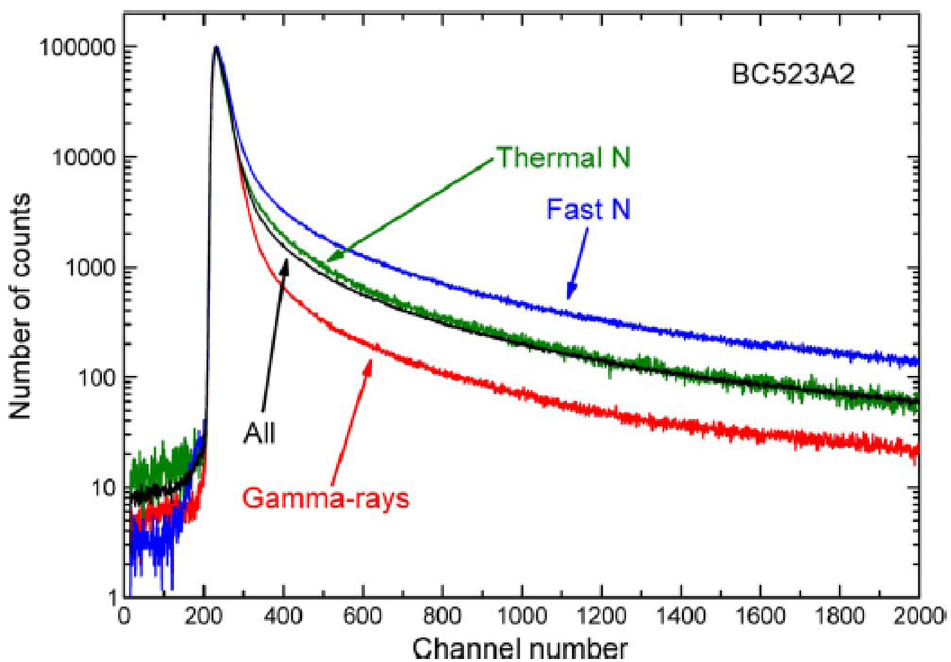


Fig. 4. Normalized light pulse shapes obtained for different gates set at the data recorded with BC523A2 scintillator and at 500 ns TAC range.

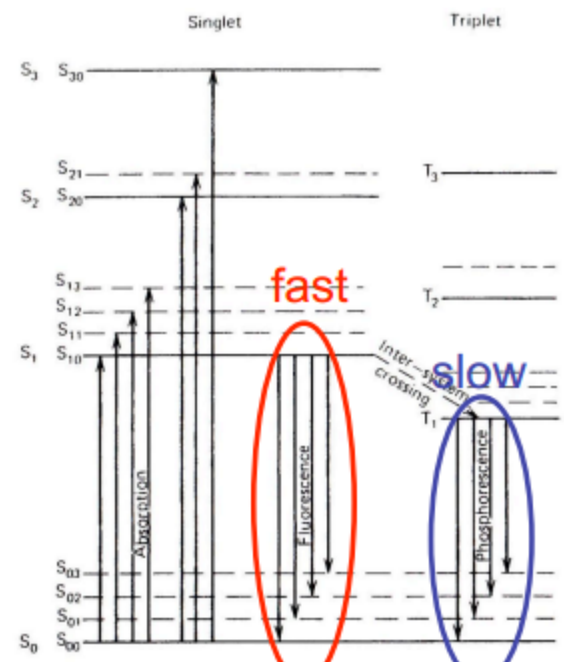
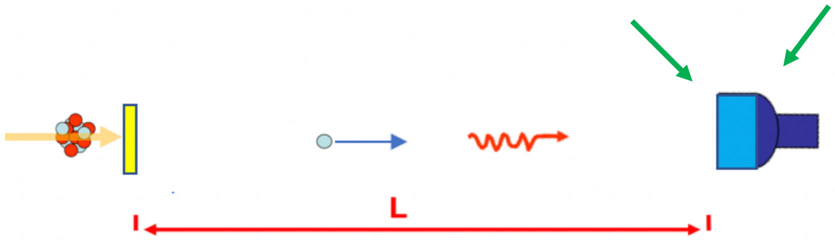


Figure 8.1 Energy levels of an organic molecule with π-electron structure. (From J. B. Birks, *The Theory and Practice of Scintillation Counting.* Copyright 1964 by Pergamon Press, Ltd. Used with permission.)

n-gamma discrimination by liquid scintillator (BC501A)



T_0 T_s

$$t \approx (T_s - T_0)$$

$$v = \frac{L}{t} \Rightarrow E = mc^2(\gamma - 1) \cong \frac{1}{2}mv^2$$

n-gamma by TOF measurement

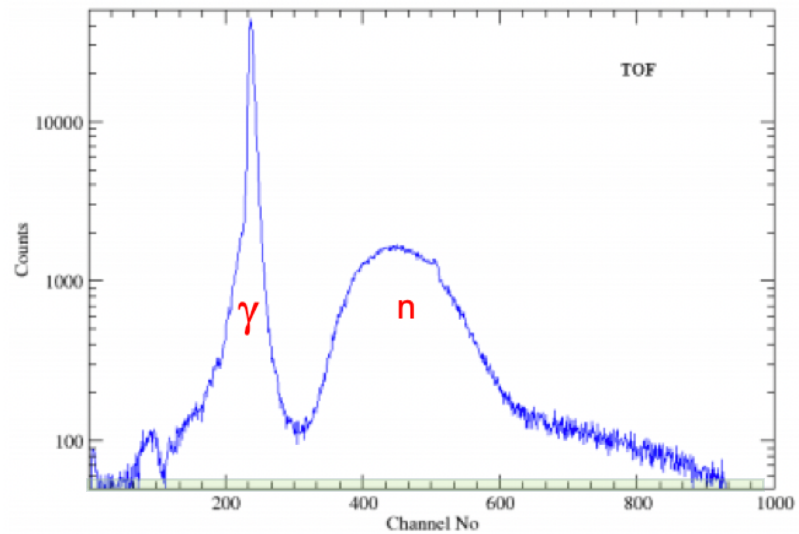
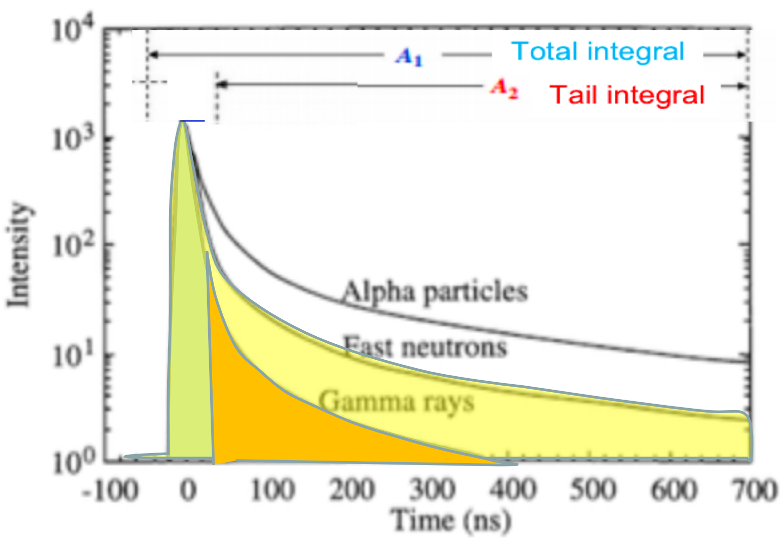
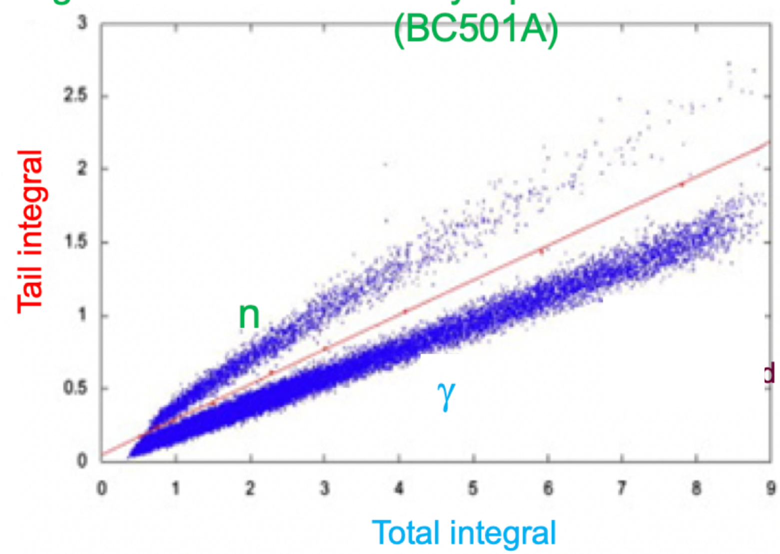


Fig-5: TOF Spectra

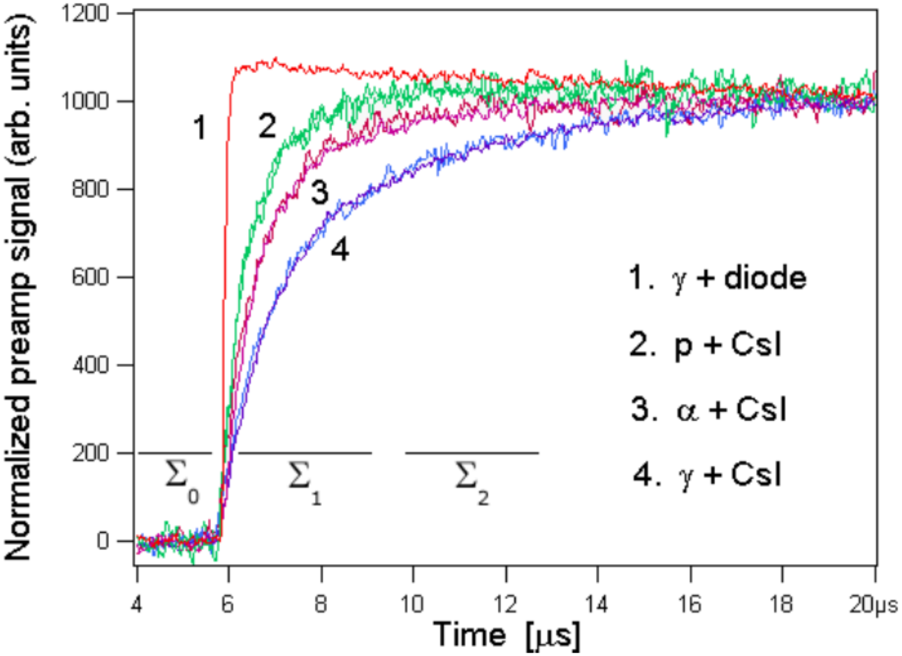
A: Area under the curve for a given range

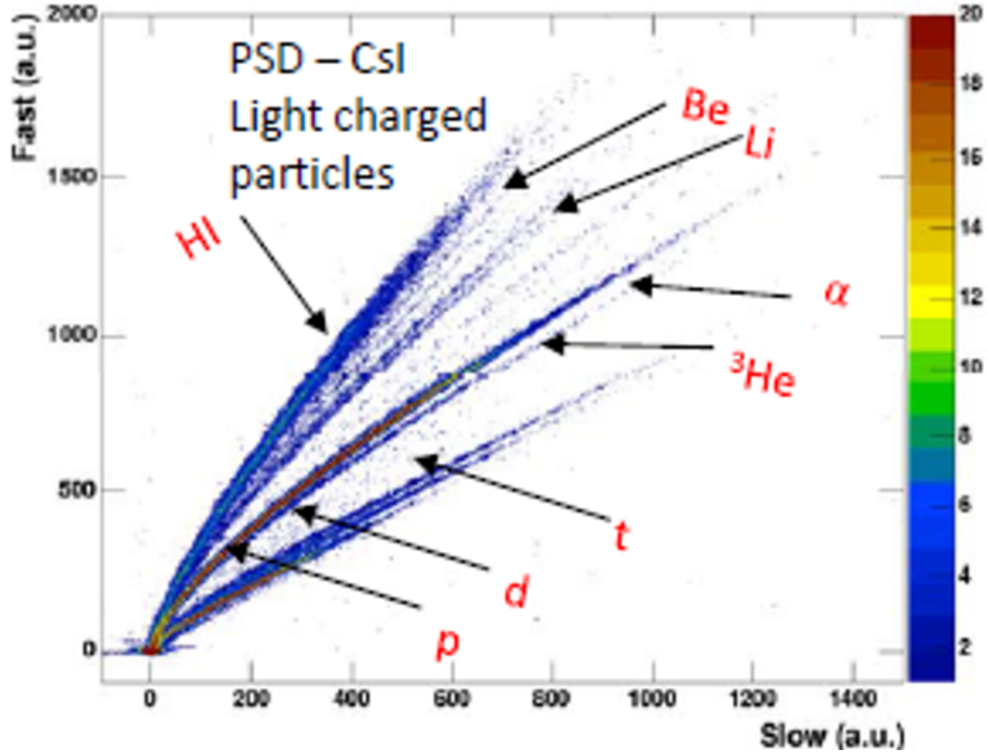


n-gamma discrimination by liquid scintillator (BC501A)



- inorganic crystals:
  - high ionization density favours exciton formation and efficient transfer to activators with fast fluorescence
  - low dE/dx has a relatively greater fraction of slow metastable states





phoswich detectors

Combination of fast scintillator + slow scintillator

plastic etc. CsI(Tl) etc.

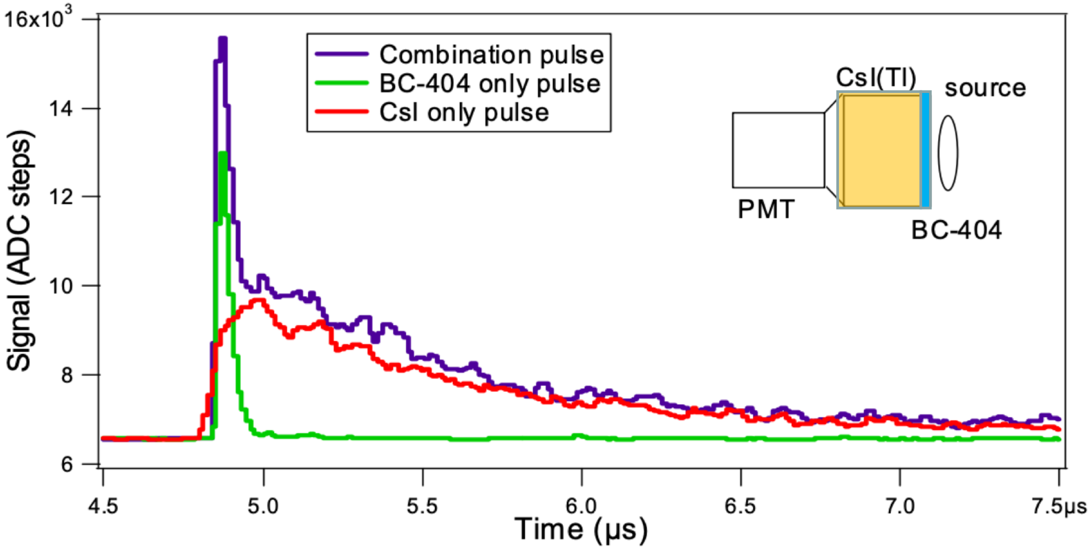
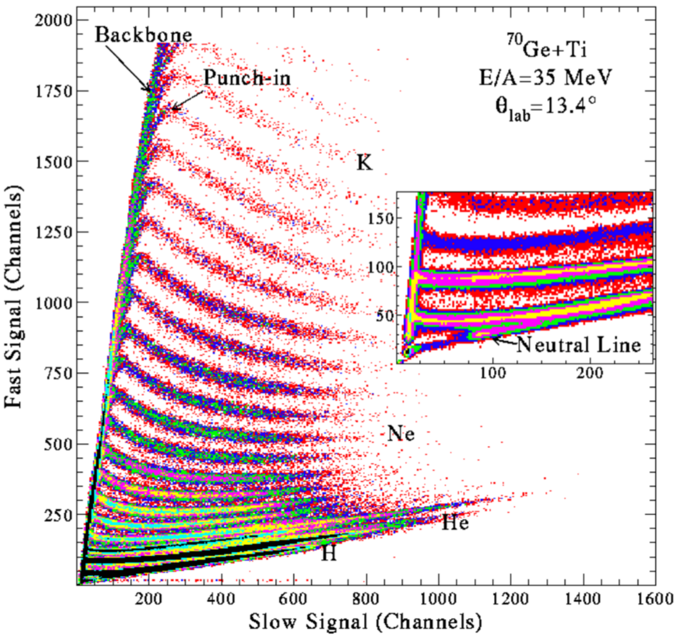
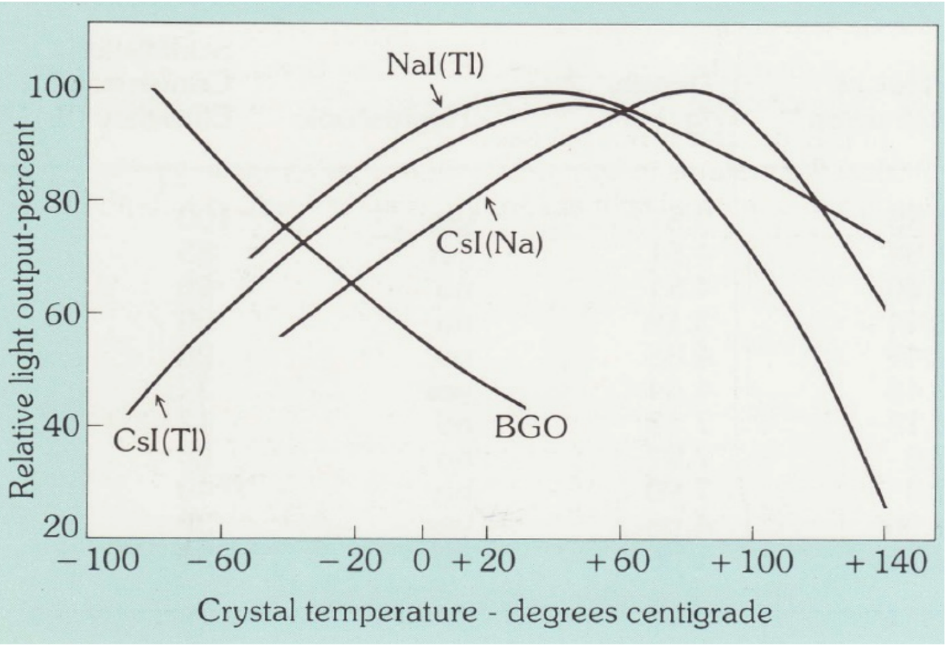


Figure 1: Pulse waveforms from the prototype phoswich detector (shown in insert). There are three types of events: CsI only pulses, BC-404 only pulses and combination pulses depositing energy in both parts of the phoswich detector.



Temperature dependence

The probability of exciton's de-excitation through photon emission is a function of temperature → Scintillator performance is a function of temperature



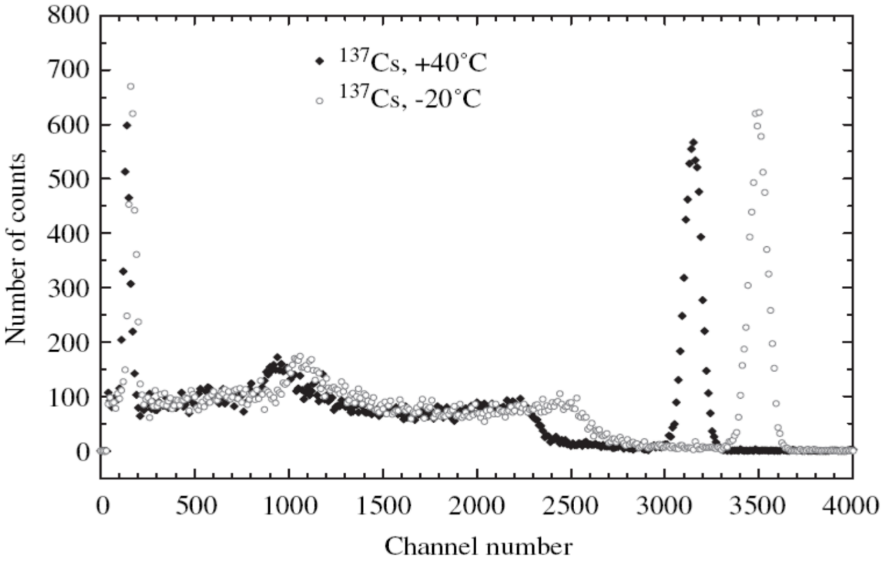


Fig. 5. The energy spectra of γ-rays from a ^{137}Cs source measured with the $LaBr_3$ crystal at −20 and 40 °C temperatures.

- In organic scintillators the light output is practically independent of the temperature between -60° and 20°

Light collection- **Reflection**

Reflector can be either specular or diffuse

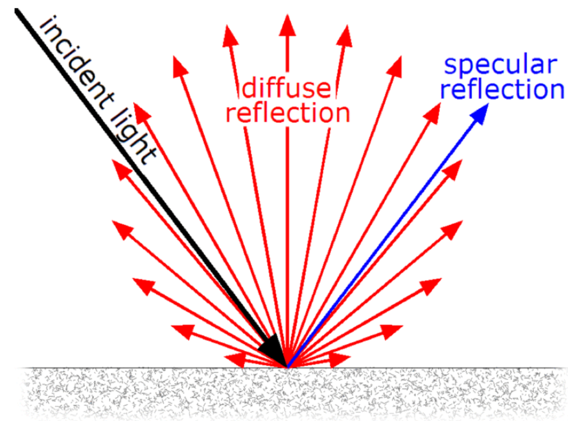
Specular reflector: mirror-like, Al foil

Diffuse reflector:

the angle of reflection is approximately independent of the angle of incidence

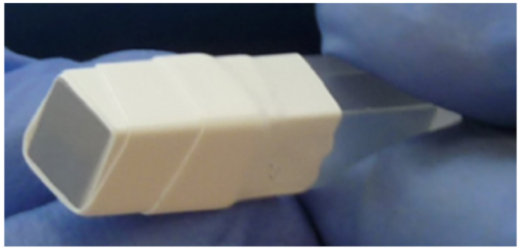
$$dI/d\theta \propto cos\theta$$

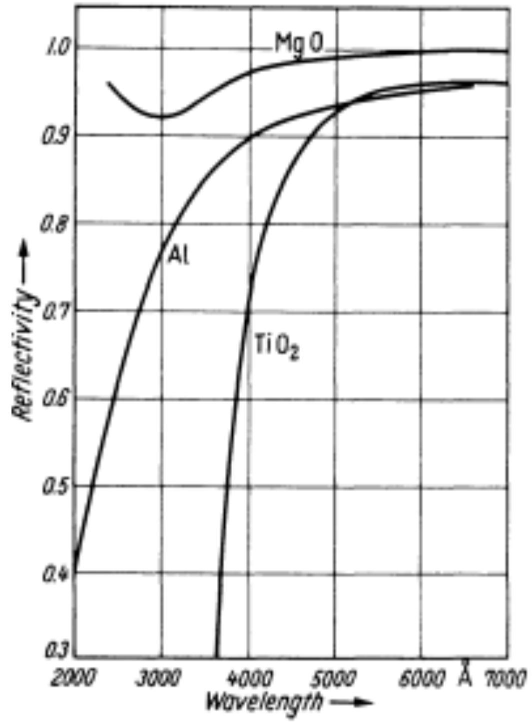
I: intensity of reflected light
θ: angle of reflection with respect to normal.



The most common diffuse reflectors:
MgO, TiO_2 and Al_2O_3 - powder or white paint

CsI(Tl), BaF_2 - Teflon foil



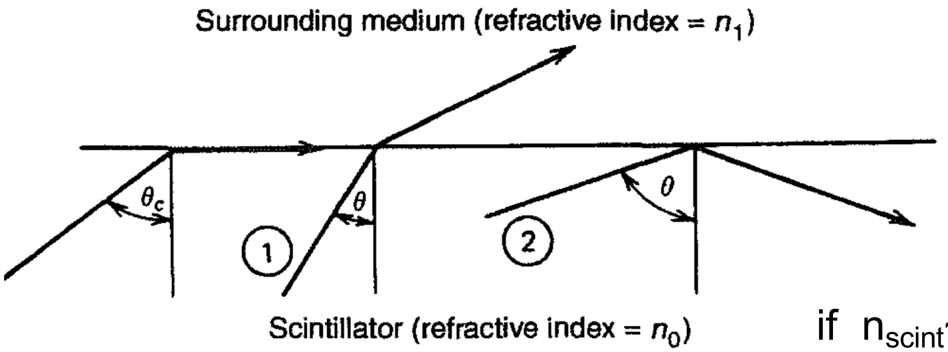


Reflectivity versus wavelength

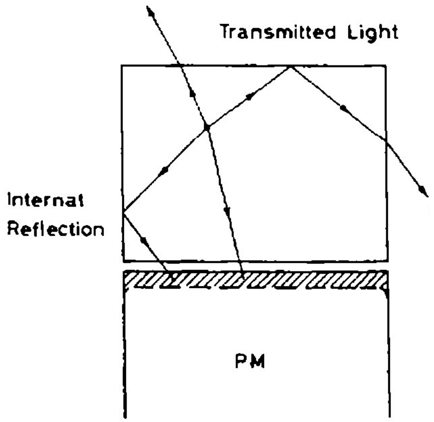
The reflectivity of TiO_2 drops sharply at ~400nm where it becomes poor reflector

Diffuse reflector are generally considered to be slightly more efficient, however, the difference is small and varies according to the geometry of the detector.

angle of total reflection



$$\sin\theta_c = \frac{n_1}{n_0}$$



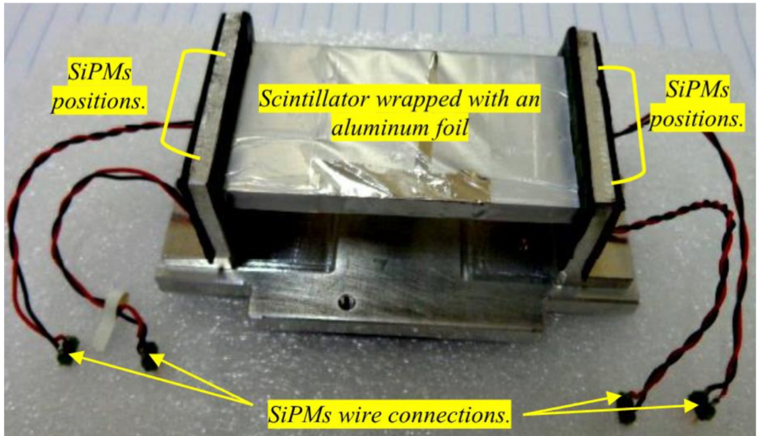
if n_{scint}~ 1.5, n_{air} ~1, θ_c~42°

If the angle of incidence θ is greater than θ_c total internal reflection will occur.

Air is the best and most convient medium.

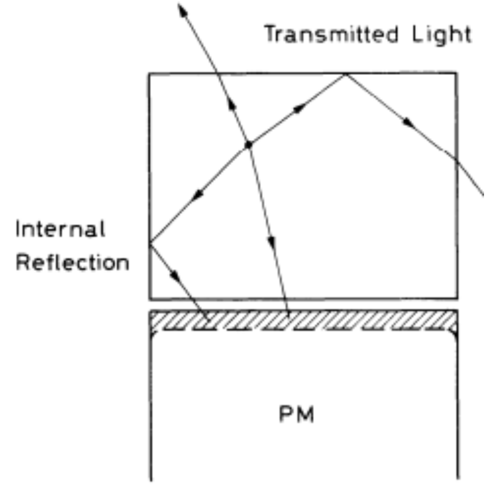
To maximize internal reflection, a layer should be left between the reflector and the scintillator. the foil should be loosely wrapped to the scintillator.

Plastic scintillator - Al foil



Coupling to the PM

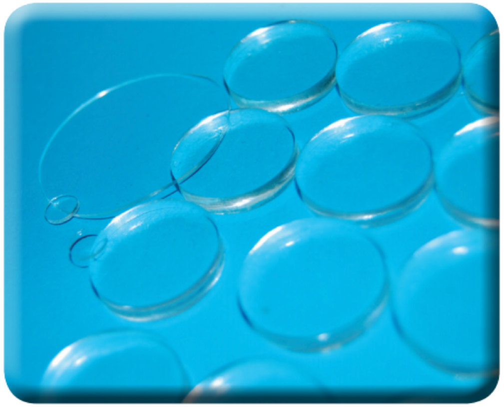
- optical glue
- optical grease
- air gap



A sharp change in the index of refraction results in a small critical angle of reflection, which in turn increases total reflection.

To avoid reflection of light from the end window of the phototube, a transparent viscous fluid is placed between the scintillator and the phototube .

The optical fluid (n~1.47) minimizes reflection because it reduces the change of the index of refraction during the passage of light from the scintillator to the phototube.



Pictured are a various sizes of optical interface pads

Light Transmission Through Light Guides

In coupling a scintillator to a photodetector through a light guide, it is tempting to couple a large area crystal to a small area detector. This could save money and also, when using photodiodes, reduce the electronic noise.

What is the efficiency of light transmission?

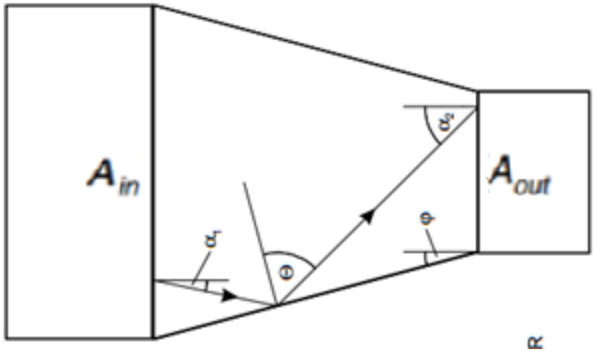
The efficiency of light transmission through a light guide is limited by

- the angle of total reflection
- conservation of phase space (Liouville's theorem)

The maximum light transferred is proportional to the ratio of surface cross sections of light guide output to input.

$$\frac{I_{out}}{I_{in}} \leq \frac{A_{out}}{A_{in}} \qquad (A_{out} \leq A_{in})$$

A ... Surface cross section
I_{in} ... total light intensity



The shape of the light guide is irrelevant. Sharp kinks have to be avoided.

Commonly used material PMMA (Polymethylmethacrylat), often with wave length shifter material added.

The light exiting scintillator on one end (rectangular cross section) needs to be guided to PMT (normally round cross section) “fish tail” shape

Keep area constant;curvature should only be weak to maintain total reflection for photons captured once (adiabatic light guide)

Light guide: flat top couples to scintillator, round bottom to photo detector.

Adiabatic light guide:

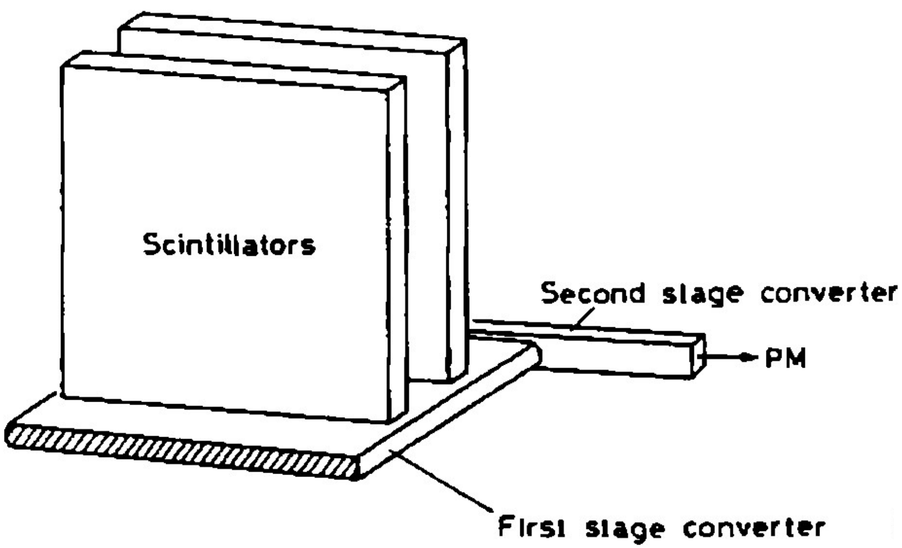
http://www.brantacan.co.uk/LightGuide1.jpg

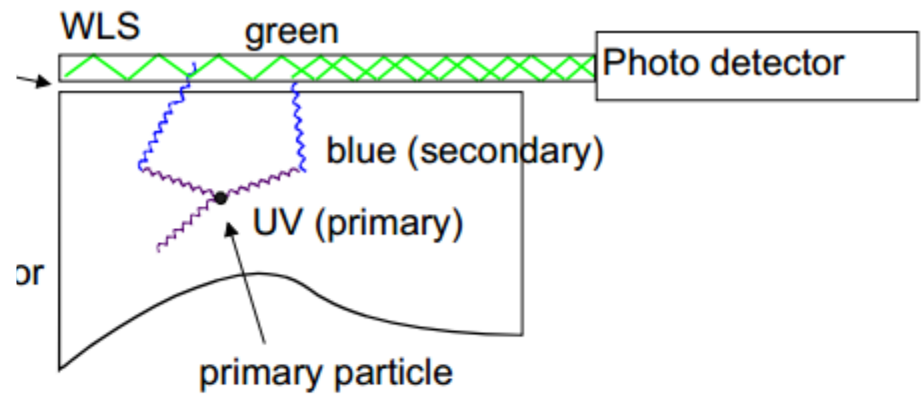
CERN Microcosm Ausstellung, Photo: M. Krammer

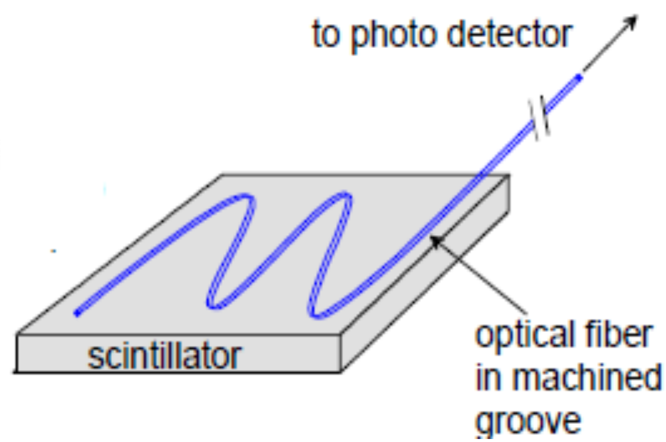
Wavelength shifter

When enough light can use 2nd wavelength shifter, e.g. along edge of scintillator plate wave length shifter rod; absorbes light leaving scintillator and reemits isotropically at (typically) green wavelength, small part (5-10 %) is guided to PMT.

Advantage: can achieve very long attenuation lengths this way







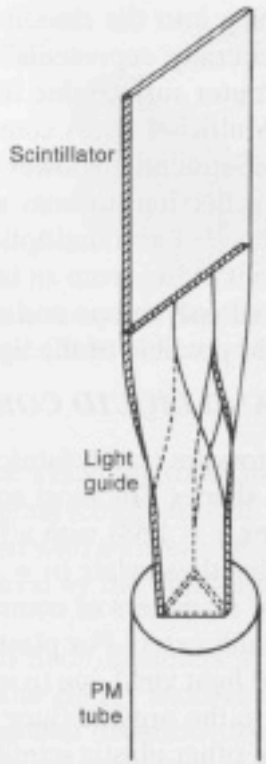


Figure 8.16 A strip light guide can be used to couple the edge of a large, flat scintillator to a PM tube.

Photon detectors

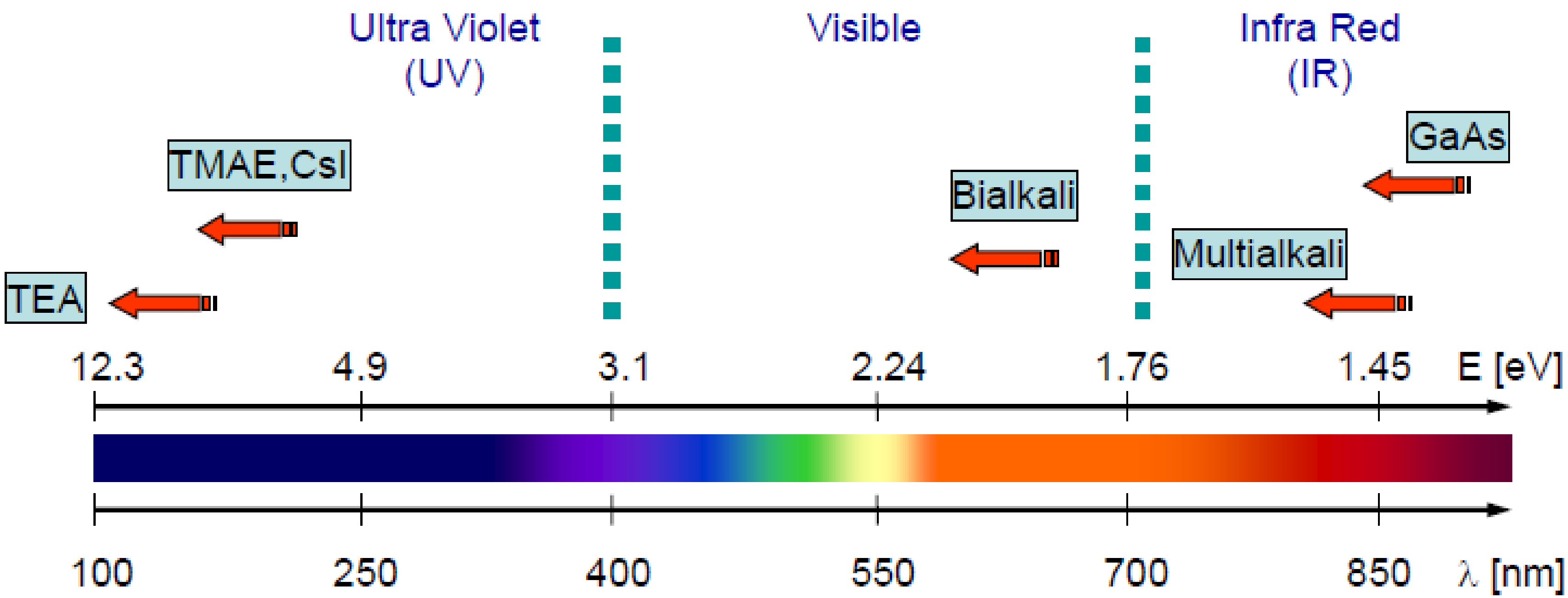
Main types of photon detectors:

- gas-based
- vacuum-based
- solid-state
- hybrid

Purpose: Convert light into detectable electronics signal

Principle: Use Photoelectric Effect to convert photons to photoelectrons

Photoemission threshold W_{ph} of various materials



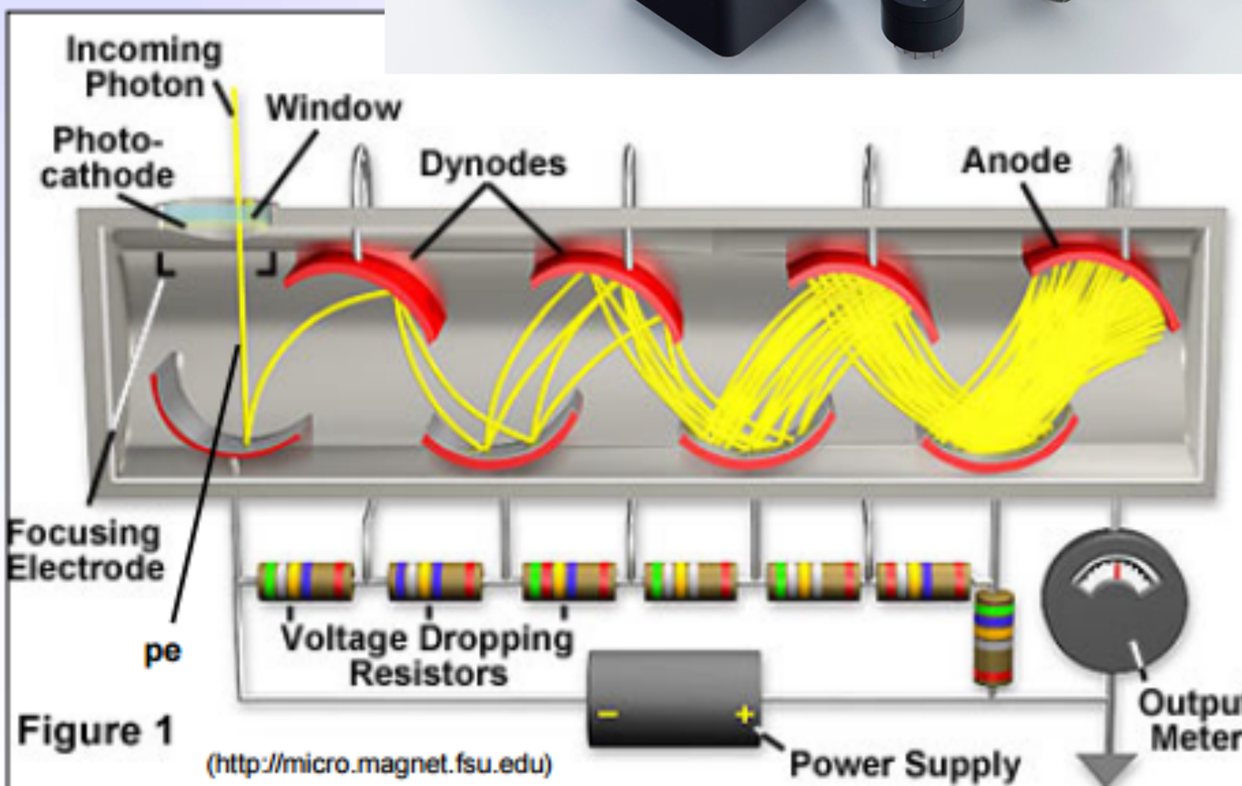
Photomultiplier tubes(PMTs)

Basic principle:

- Photo-emission from photo-cathode
- Secondary emission (SE) from N dynodes:
  - dynode gain g≈3-50 (function of incoming electron energy E);
  - total gain *M*:

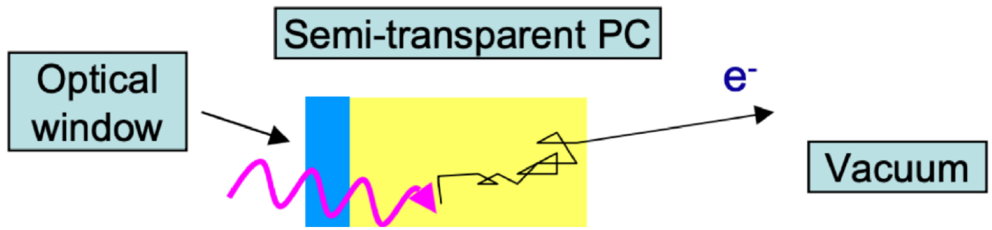
$$M = \prod_{i=1}^{N} g_i$$

- Example:
  - 10 dynodes with g=4
  - $M = 4^{10} \approx 10^6$

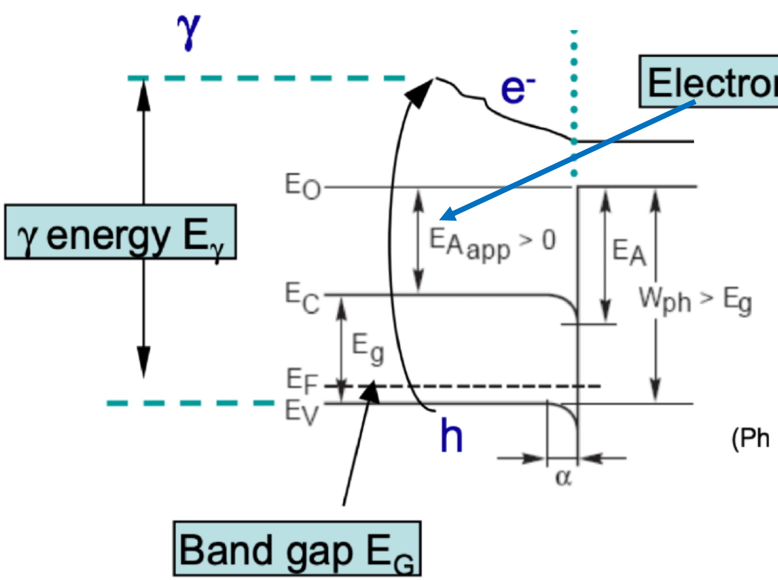


Photocathodes

- The important process in the photocathode is the photoelectric effect
  - ➢ Photons are absorbed and impart energy to electrons
  - ➢ Electrons diffuse through the material losing energy



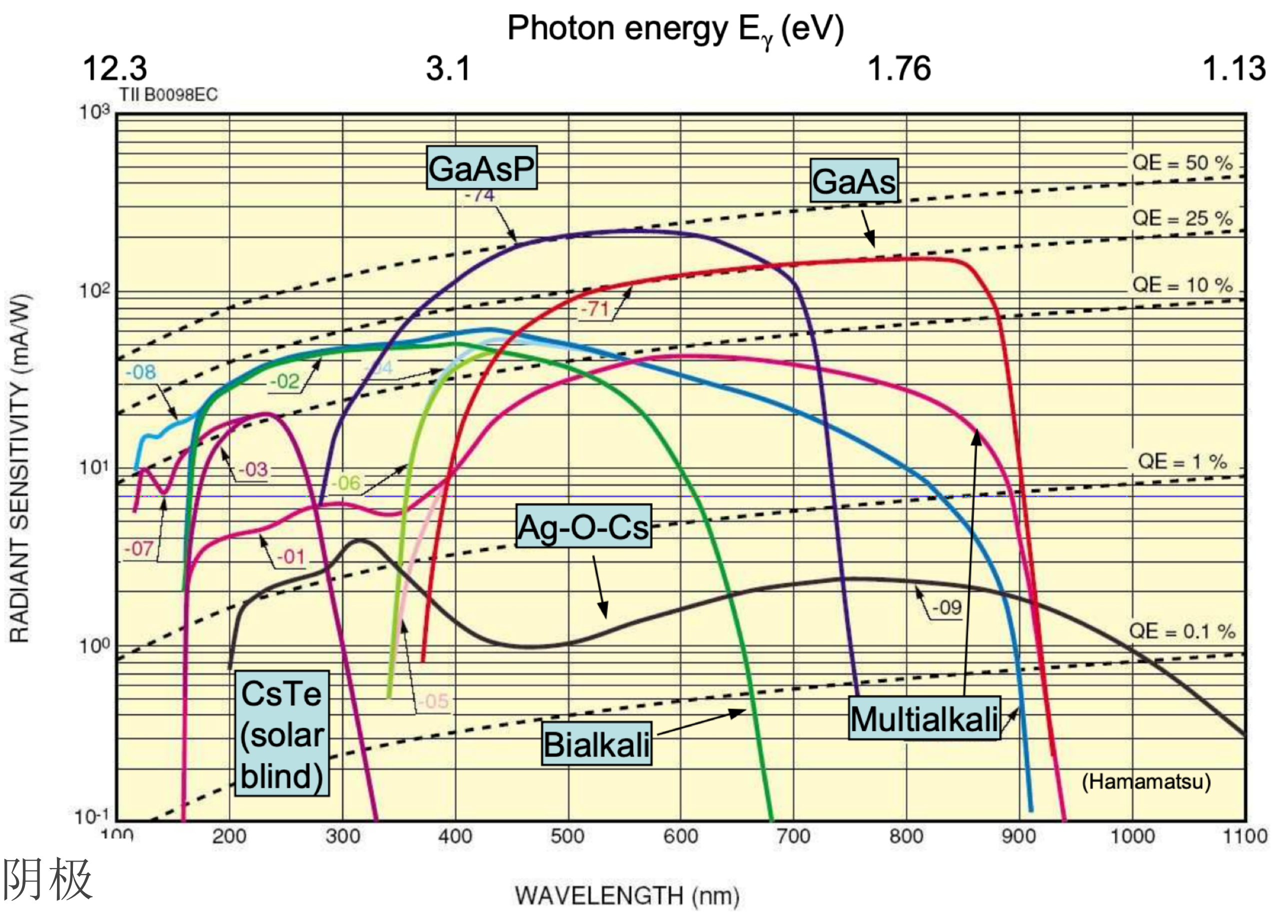
  - ➢ Electrons reaching the surface with sufficient energy escape



$$E_\gamma = h\nu > W_{ph} = E_G + E_A$$

Quantum efficiencies(QE) of typical photo-cathodes

$$Q.E. = \frac{\#\,\text{emitted photo electrons}}{\#\,\text{incoming photons}}$$



双碱阴极

Bialkali: SbKCs, SbRbCs Multialkali: $SbNa_2KCs$ (alkali metals have low work function)

- Quantum efficiency around 20-30 %
- Strong function of the wavelength of the incident light

PMT window transmittance

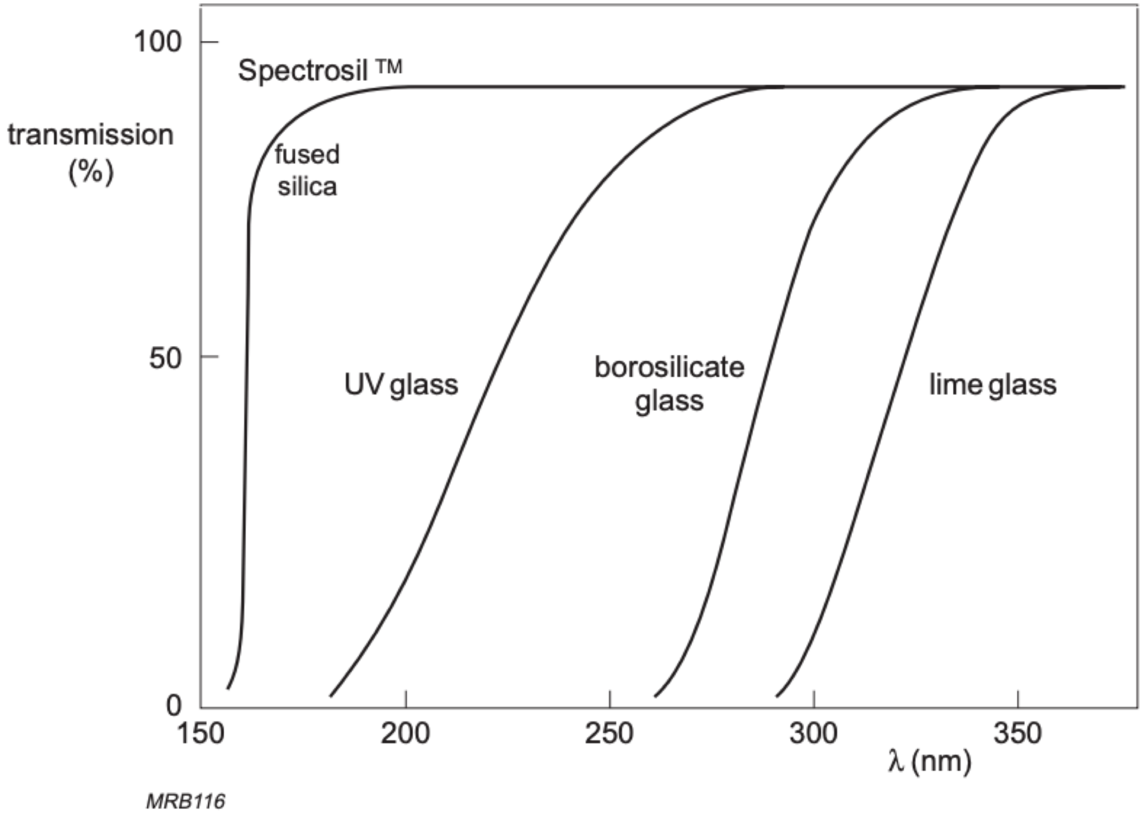
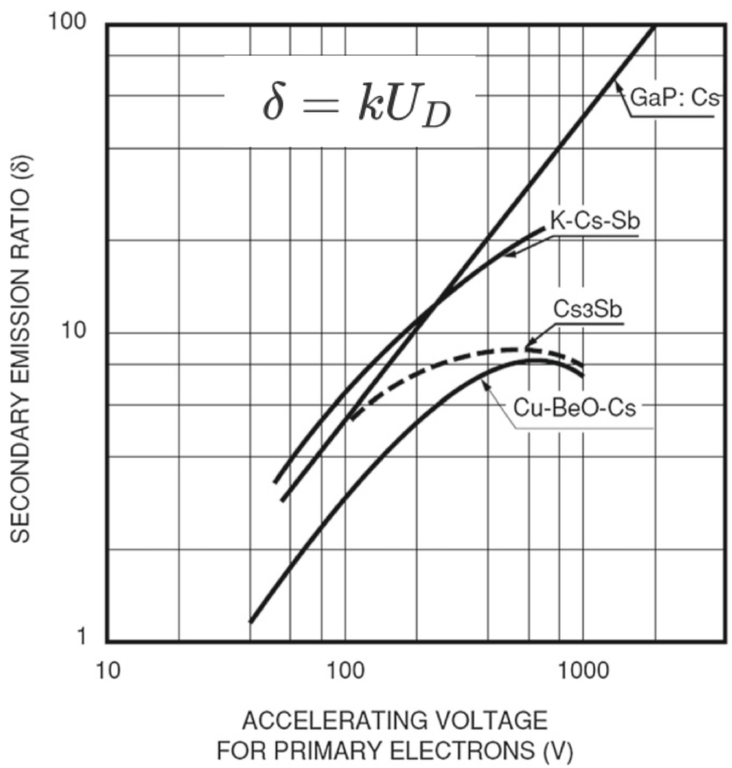
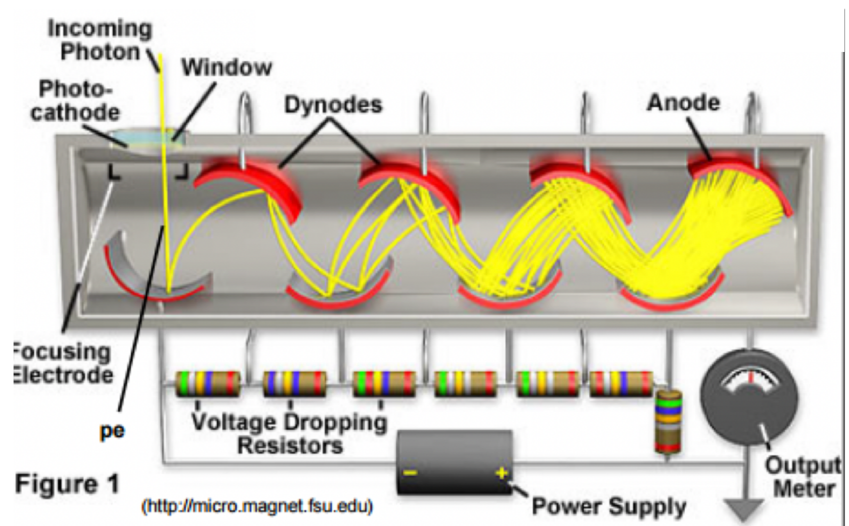


Fig.1.5 Transmission (%) as a function of wavelength λ for various glasses used in photomultiplier input windows (thickness 3 mm)

Secondary electron emission

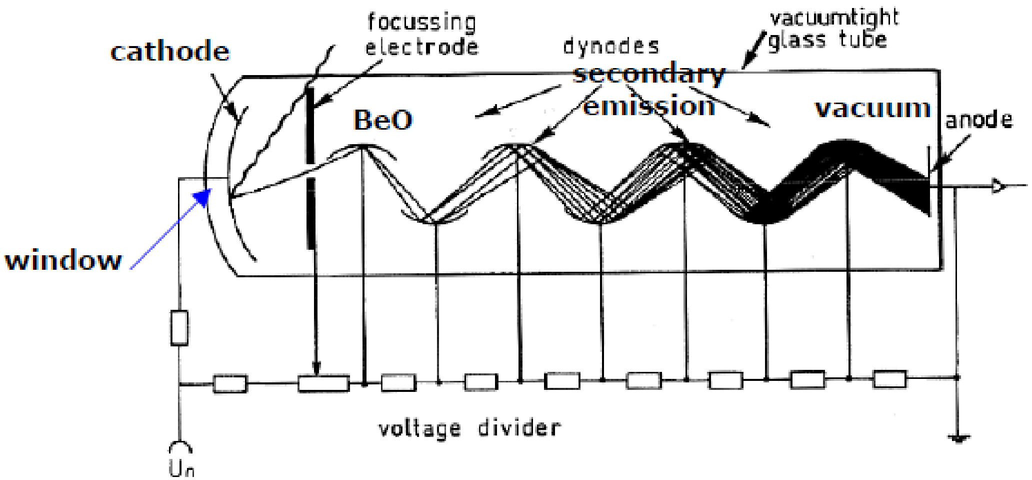
- Photoelectrons are then accelerated onto an electrode made of material of high coefficient of secondary emission, eg. BeO 3-5 secondary electrons per incident electron of 100 eV can be Achieved
- At one dynode δ = (number of secondary electrons emitted) / (primary incident electrons)
- Depends on incident electron energy

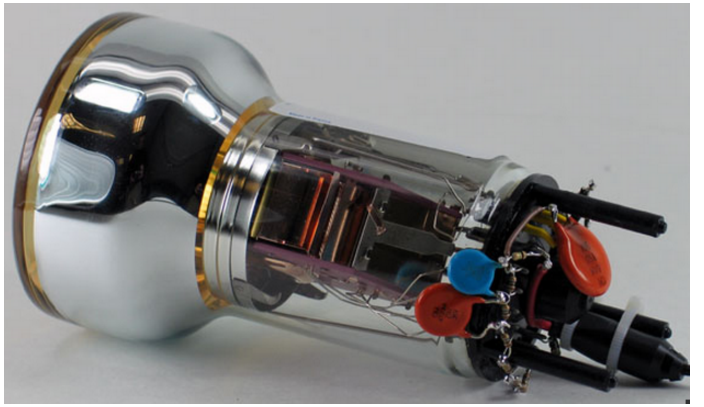




Gain : $G = \delta_1 \cdot \delta_2 \cdot \delta_3 \cdots \delta_n$

Voltage dividers





HV can be positive or negative,

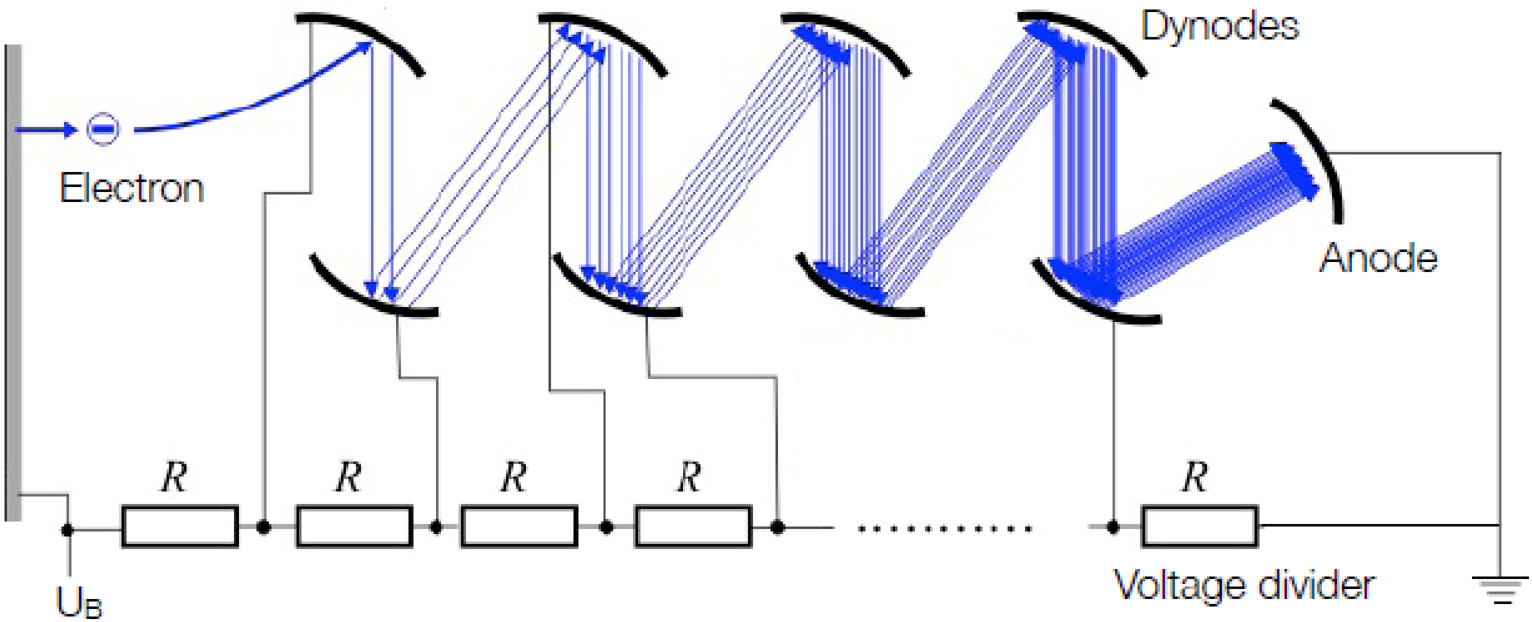
if anode is +HV, "AC-coupled";

if anode is GND, "DC-coupled", cathode is –HV … glass becomes charged

Voltages are distributed to the dynodes by a resistive voltage divider,

variations such as active designs (with transistors or diodes) are also possible.

Photomultipliers – Dynode Chain



Multiplication process:

Electrons accelerated toward dynode
Further electrons produced ➔ avalanche

Secondary emission coefficient:
δ = #(e⁻ produced)/#(e⁻ incoming)

Typical: $\delta = 2 - 10$, $n = 8 - 15$ ➔ $G = \delta^n = 10^6 - 10^8$

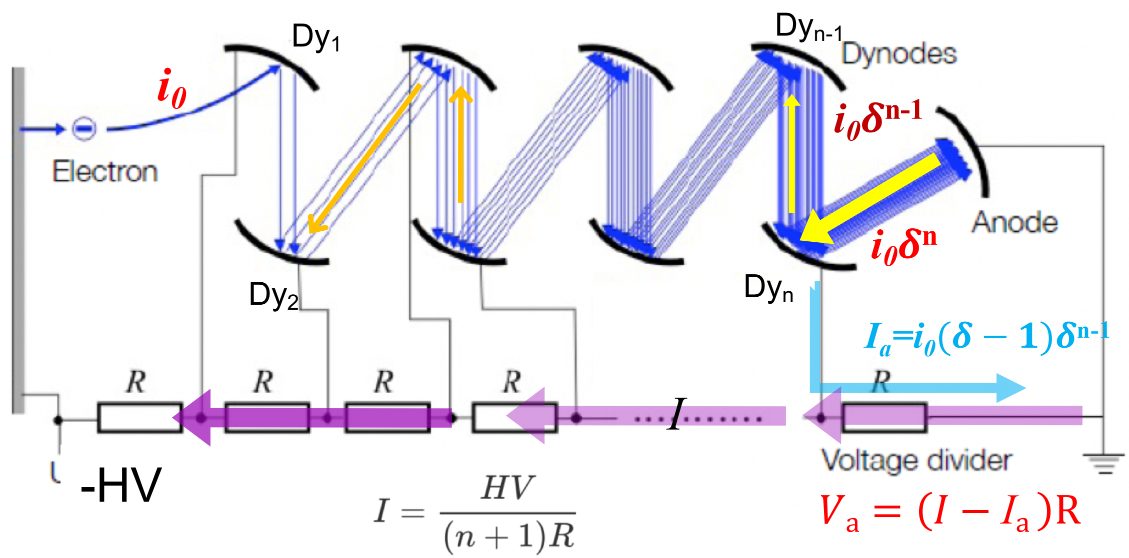
Gain fluctuation: $\delta = kU_D$; $G = a_0(kU_D)^n$

$$dG/G = n\,dU_D/U_D = n\,dU_B/U_B$$

For n=10, 1% change in U_B, 10% variation in gain.

Supply voltages are regulated to better than 0.05%

The problem of simple resistive voltage divider



Example: Estimate the anode current in typical PMT of NaI(Tl) scintillator.

PMT : $\eta = 0.25, \quad M = \delta^n = 10^6$

HV=2kV, (n+1)R=7x100kΩ = 0.7M, $I = 3\text{mA}$

NaI(Tl) ~ 40k photons/MeV, $\tau = 230ns$

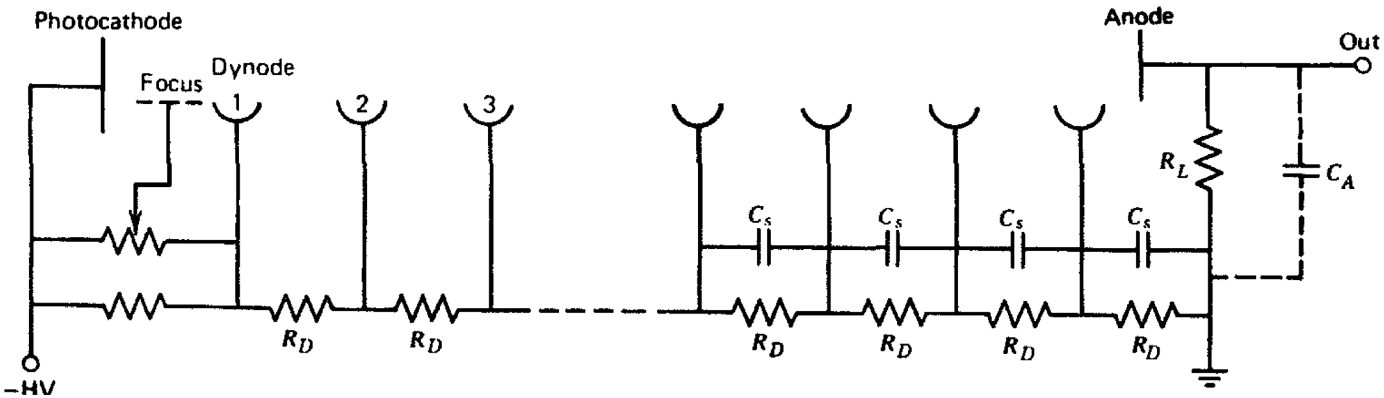
$$i_0 \sim \frac{40\text{k} \times e^- \times 0.25}{230ns} \quad \text{for a pulse of 1MeV}$$

$$I_a = \frac{dQ}{dt} \sim i_0 \times 9 \times 10^5 = 7 \times 10^{-3} A = \mathbf{7\ mA}!$$

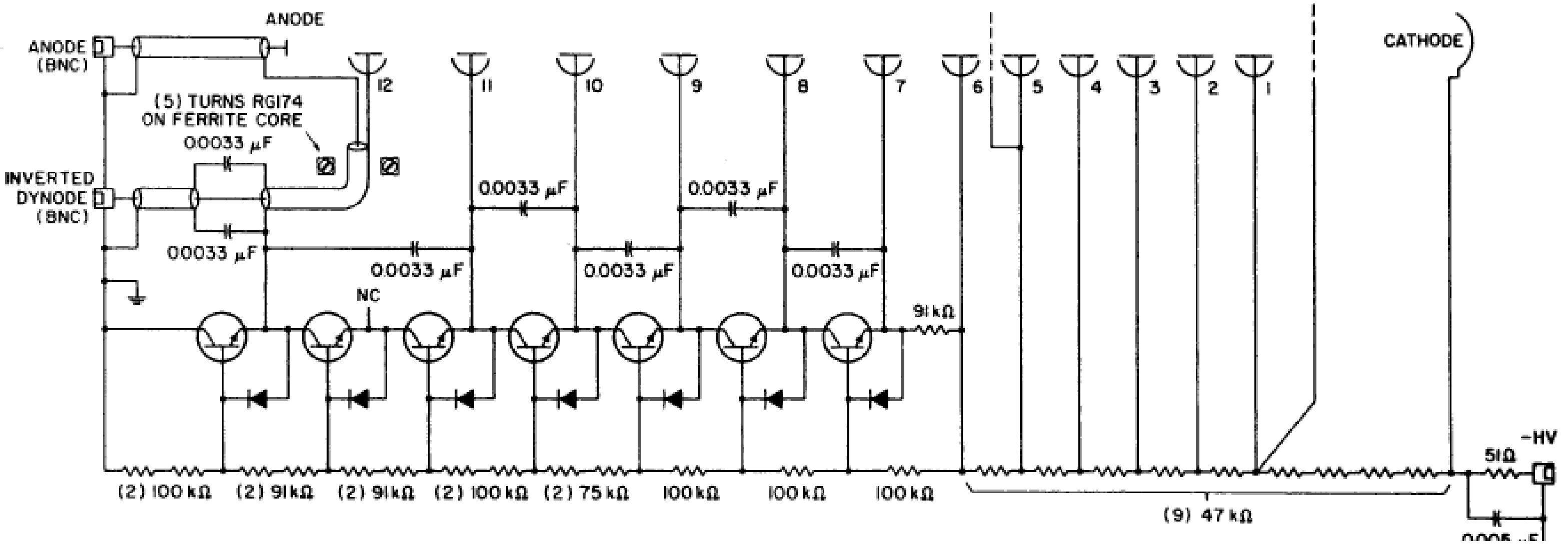
$$V_a \downarrow = (I - I_a \uparrow)R \to G \downarrow$$

DC current through resistive divider must be much greater (>10x,preferably more) than the average signal current. $I > 10 \times I_a$

To prevent this problem, decoupling capacitors can be used to the last few states. These capacitors supply PMT with an electric charge during the forming of signal pulse and restrain the voltage drop between the last dynode and the anode, resulting in a significant improvement in pulse linearity.



Scintillators with higher light output or running at higher rates might require 10 mA, which becomes thermally problematic.
In these cases, voltage dividers transistor current buffers are often used.



The voltage distribution in the dynode chain can be optimized for

- high gain
- time resolution
- good linearity up to high peak currents

Recommended voltage distributions can be found in the manufacturers data sheets.

Independent power supply for last two or three dynode for very high current pulse.

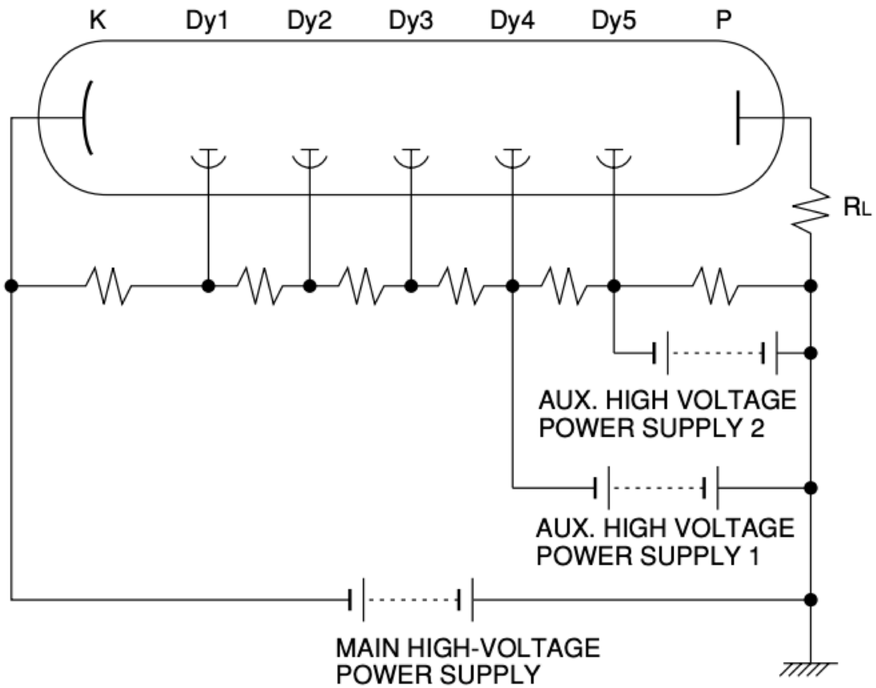


Figure 5-7: Booster circuit

Voltage Divider Circuit Using Multiple Power Supplies (Booster Method)

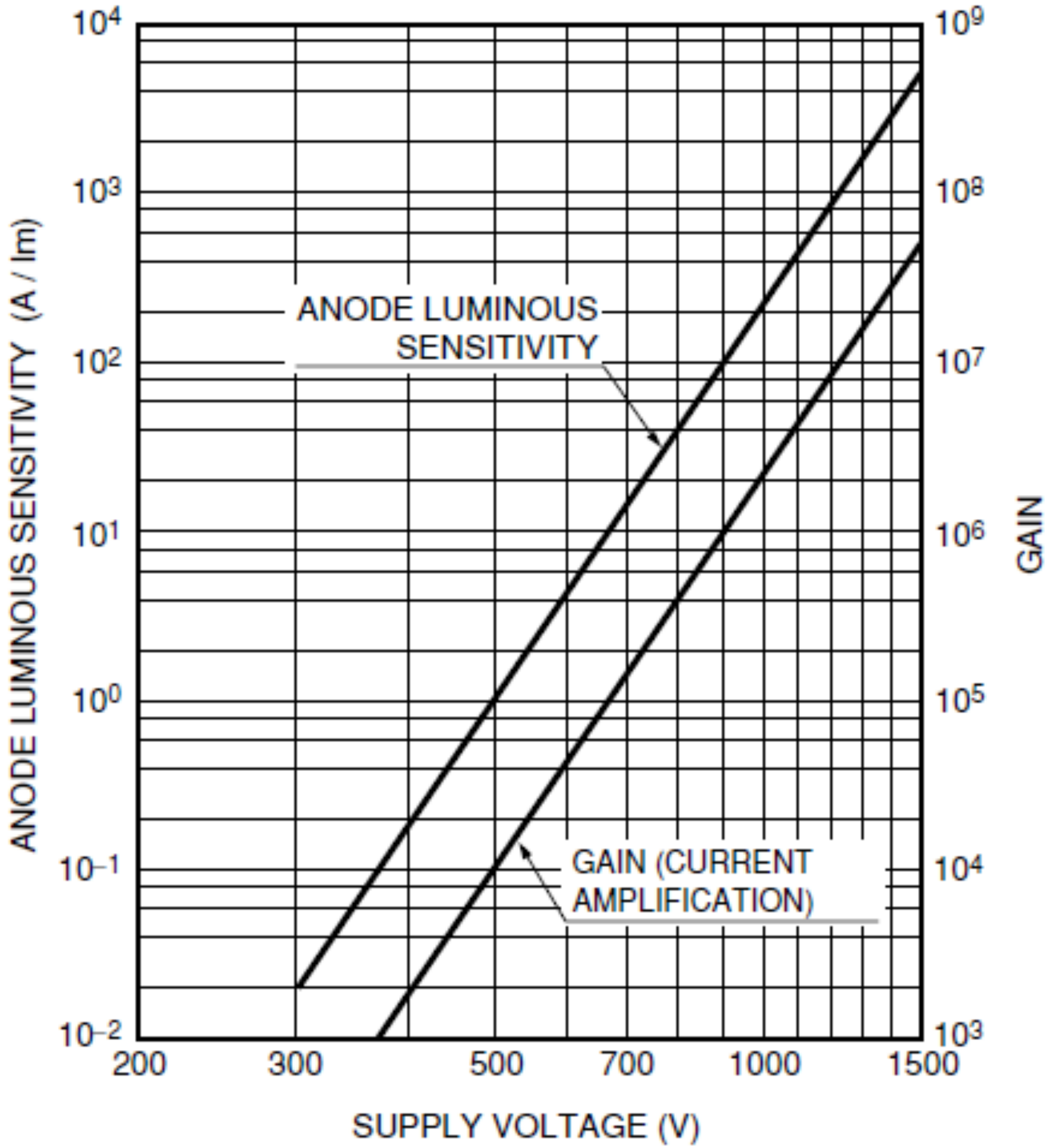


Figure 4-13: Gain vs. supply voltage

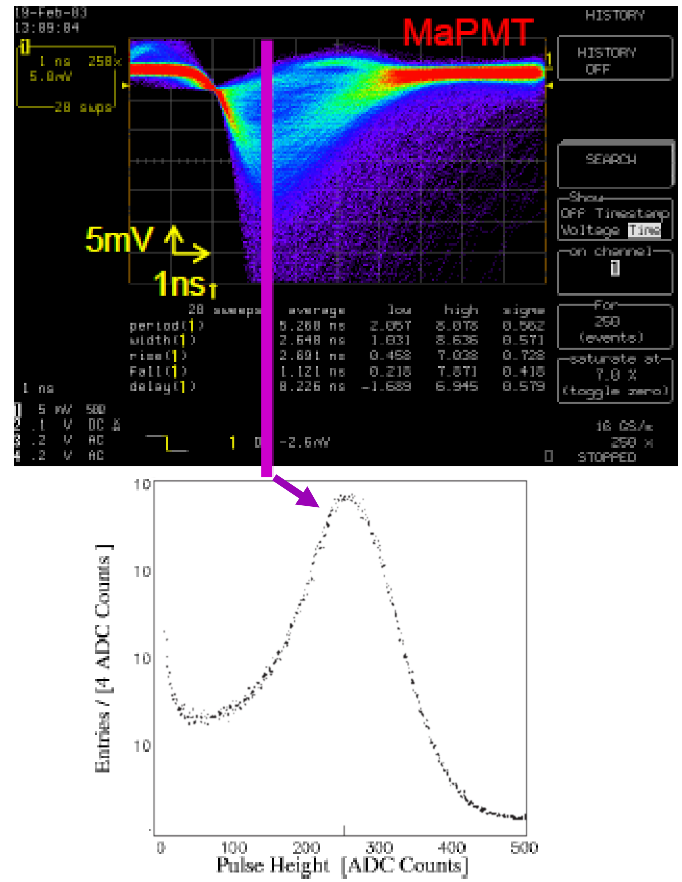
$$logA \propto logV$$

Single Photoelectron Spectrum

PMTs can be run in high-gain modes that are sensitive to single photoelectrons. In such cases the anode current must follow a Poisson distribution characterized by a mean and width of 'one.' Multiple photoelectrons can be easily distinguished.

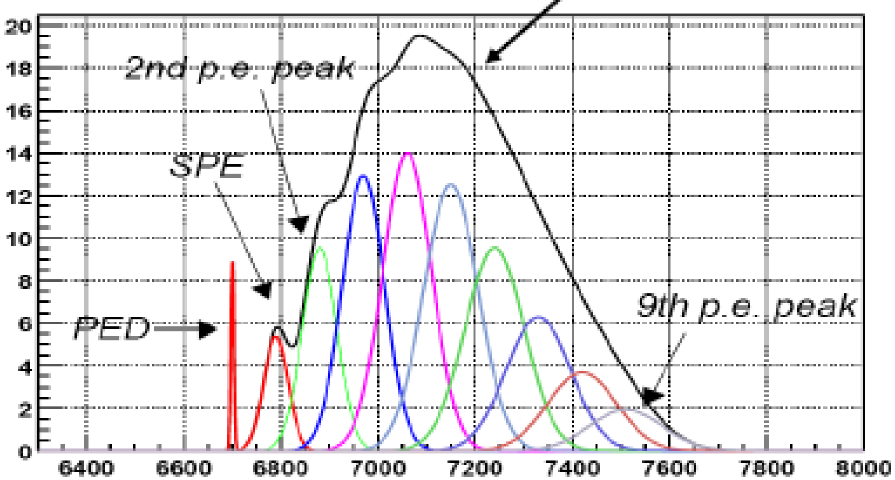
single photon events to oscilloscope (50Ω)

Only single photoelectron events –



charge integration → pulse height spectrum

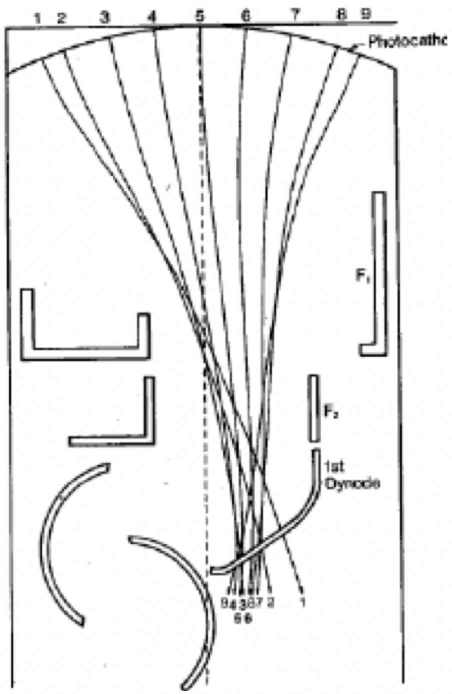
Curve from many events made up from individual events with discrete numbers of photoelectrons.

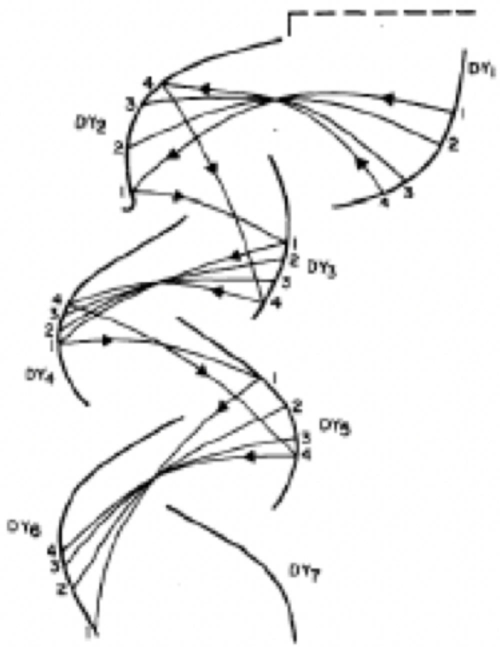


From C.Andreopoulos, et al. NuMI-ANA-994 US/PHYS/HEP/18-10-2001

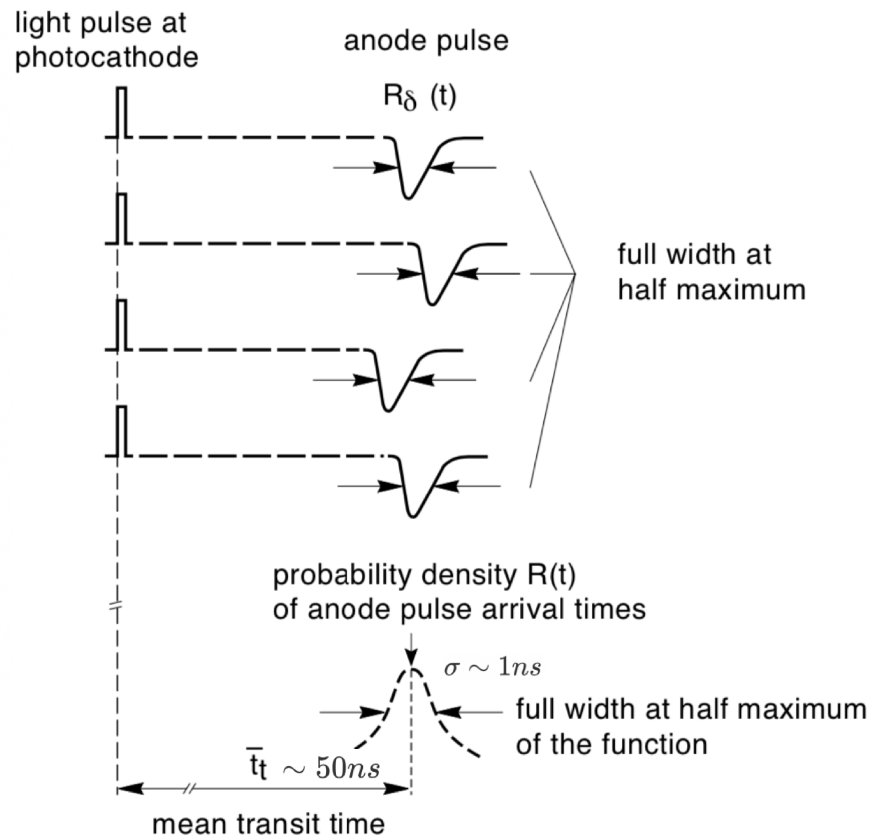
PMTs - time distribution

The interval between the arrival of a light pulse at the cathode and that of the corresponding current pulse at the anode is called the transit time. 渡越时间





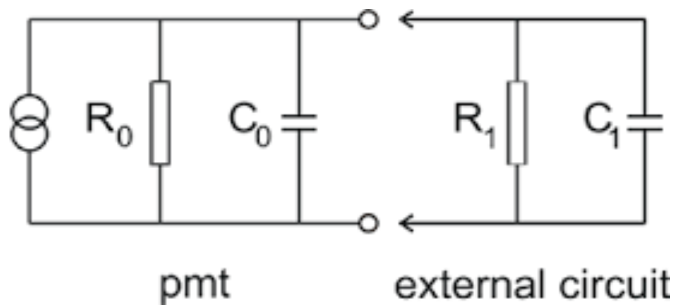
Response-pulse jitter due to transit time fluctuations



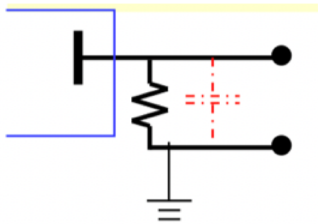
PMT's DC pulse shape

The equivalent circuit for a photomultiplier is a current generator, in parallel with resistance, R_o, being much greater than $10^9\Omega$ and with stray capacitance, C_0, about 5 pF. $R \sim R_1$ and $C = C_1 + C_0$

$$i(t) = \frac{Q_0}{\tau_s} e^{-\frac{t}{\tau_s}}$$



τ=RC

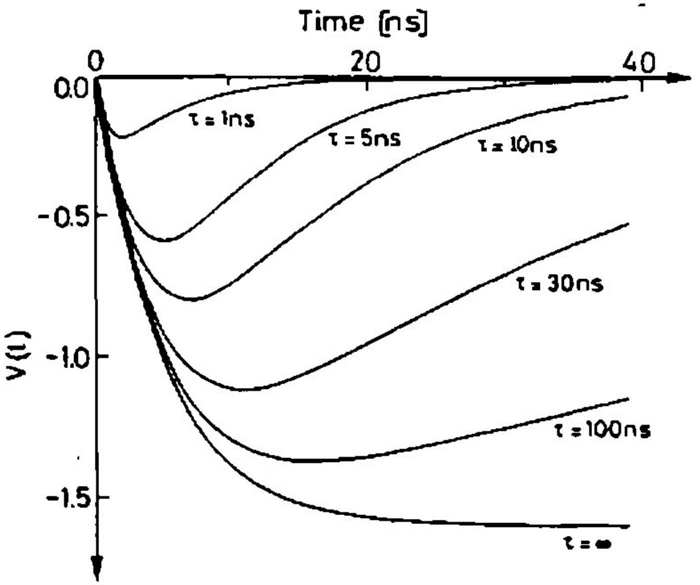


$$i(t) = -\frac{V}{R} + C\frac{dV}{dt}$$

$$V(t) = -\frac{Q_0 R}{\tau - \tau_s}\left[e^{-\frac{t}{\tau_s}} - e^{-\frac{t}{\tau}}\right] \quad ,\tau \neq \tau_s$$

$$V(t) = -\frac{Q_0 R}{\tau_s^2} t e^{-\frac{t}{\tau_s}} \quad ,\tau = \tau_s$$

$G = 10^6$, $N = 100$, $C = 10$ pF and $\tau_s = 5$ ns,

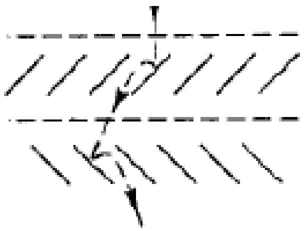


Dynode configurations of PMT's

- simple design
- good for large PC ∅

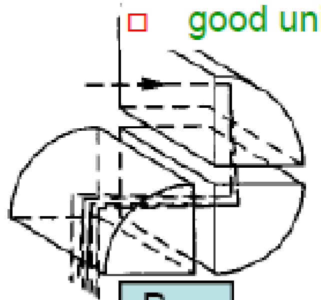
Traditional

百叶窗

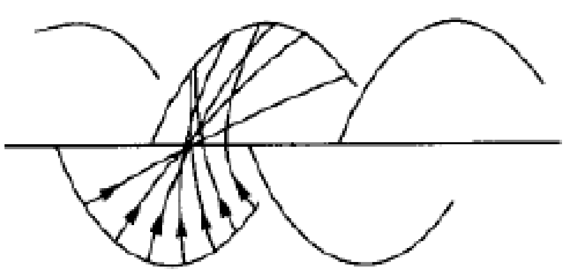


Venetian blind

- best photoelectron collection efficiency
- good uniformity

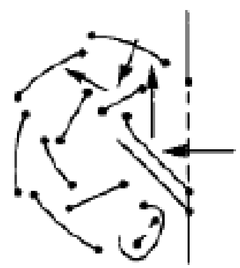


Box



Linear focussing

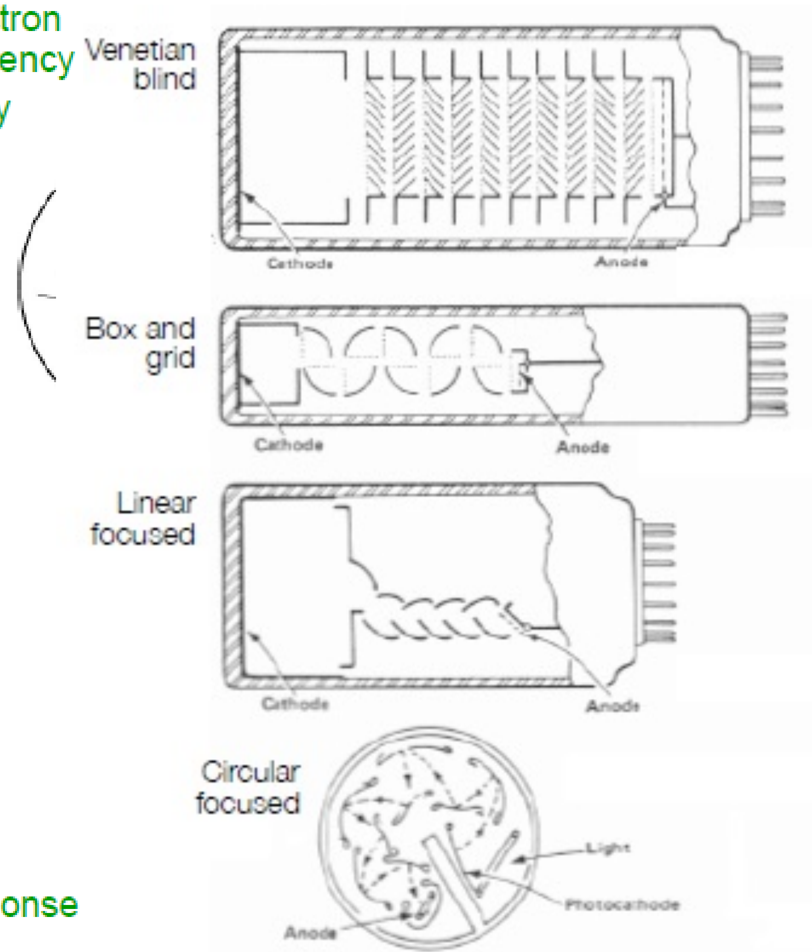
(Photonis)



Circular cage

- excellent linearity
- good time resolution
- fast time response

- compact
- fast time response

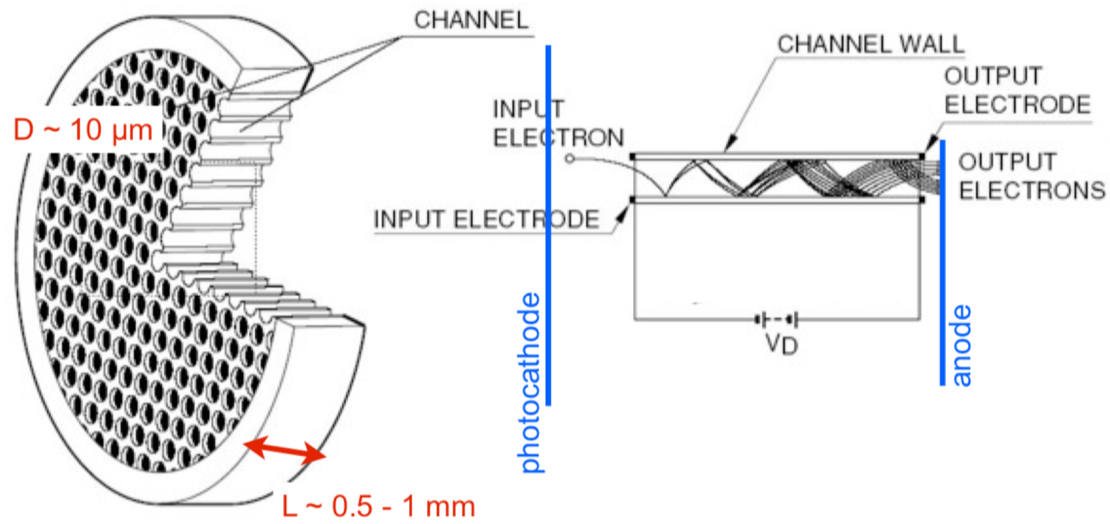


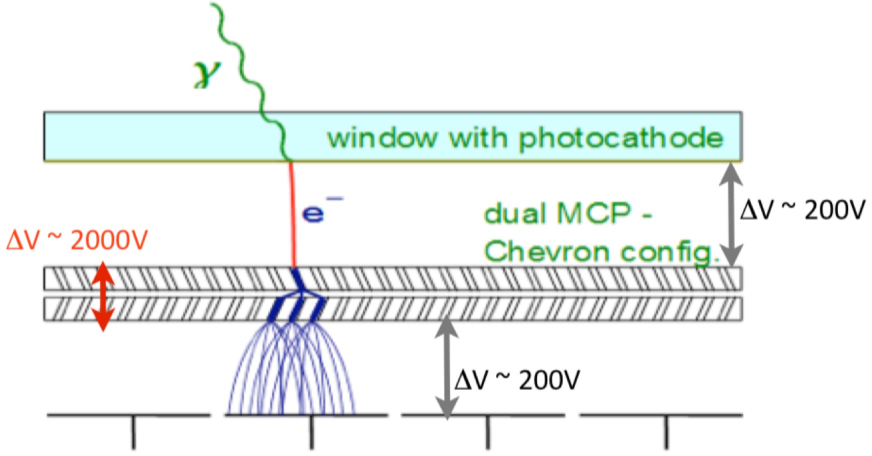
PMT's are in general very sensitive to magnetic fields, even to earth field (30-60 μT).

➔ Magnetic shielding required.

Micro channel plates (MCP) PMTs

- lead glass plate
- perforated by arrays of cylindrical holes ("micro-channels")
- inner surface of each channel = **continuous dynode**
- δ ~ 2 / strike
- Gain = f (Length/Diameter)
- typical L/D ~ 40 => ~ 10 strikes => **Gain** = 2^{10} **~ 10^3 (single plate)**





typical configuration: Chevron configuration.
- 2 MCP => **Gain ~ 10^6**
- segmented anode possible => position sensitive

Advantages wrt PMT :

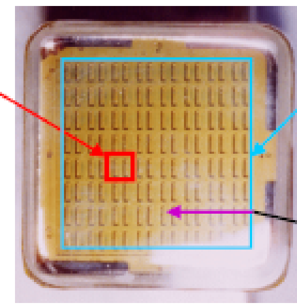
excellent timing resolution (σ ~ 40 ps)
B tolerant (0.1 T random direction ; ~ 1T axial dir.)
position sensitive (if segmented anode)
better single pe (if operated in saturation mode)

Limitation :

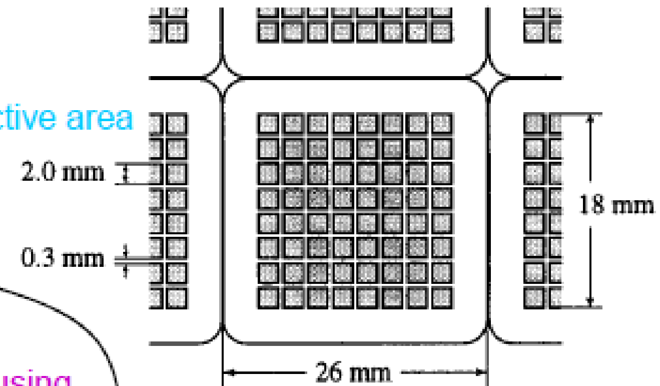
severe aging effect (due to ion feedback)
limitation on count rate (long recovery time)

Multi-anode Photo Multiplier Tubes

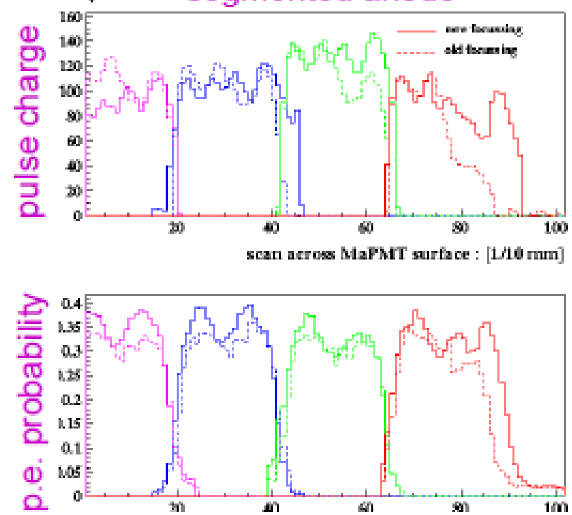
- Position sensitive PMT:
  - 8x8 metal channel dynode chains in one vacuum envelope (26×26 mm^2)
  - segmented anode: 2×2 mm^2
  - active area fraction: 48%
- UV glass window
- Bialkali photo cathode:
  - QE = 22…25% at λ = 380 nm
- Gain:
  - $G = 3 \cdot 10^5$ at 800 V
- Uniformity, Crosstalk:
  - much improved wrt. first attempts
- Applications:
  - medical imaging
  - HERA-B, COMPASS: Ring Imaging Cherenkov counters

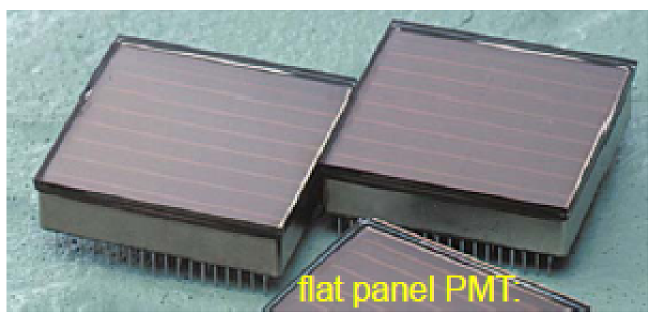


MaPMT window & electron focusing



segmented anode

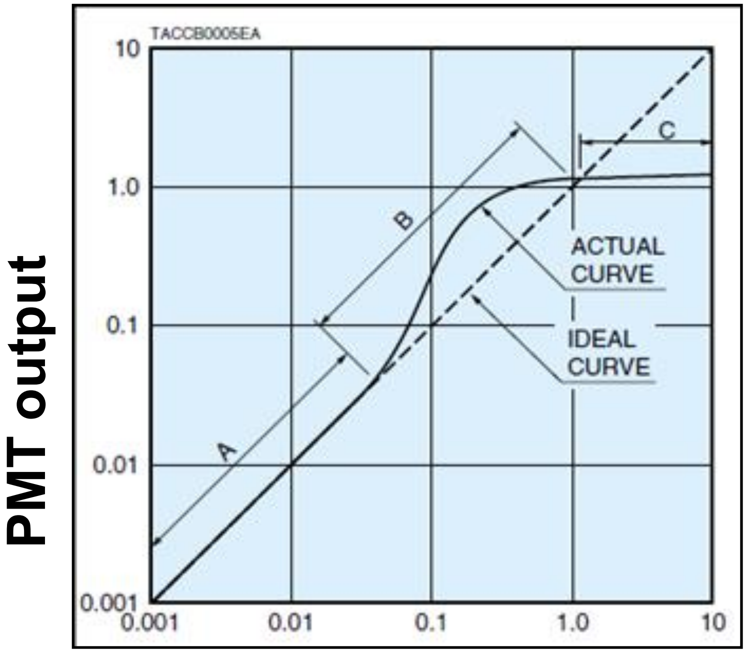




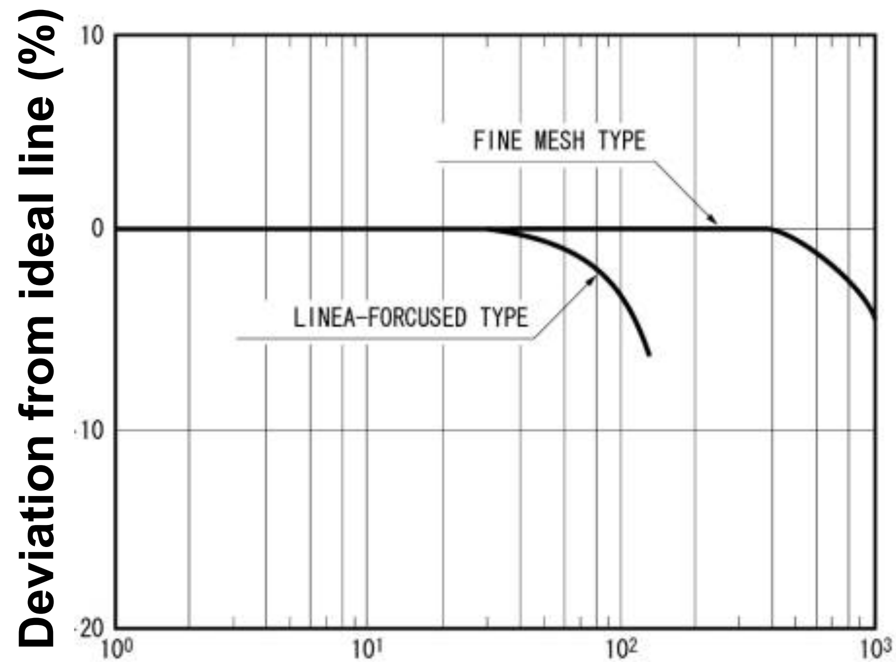
next generation MaPMT

linearity

Relation between radiation energy and PMT output.



Radiation Energy
Light Intensity

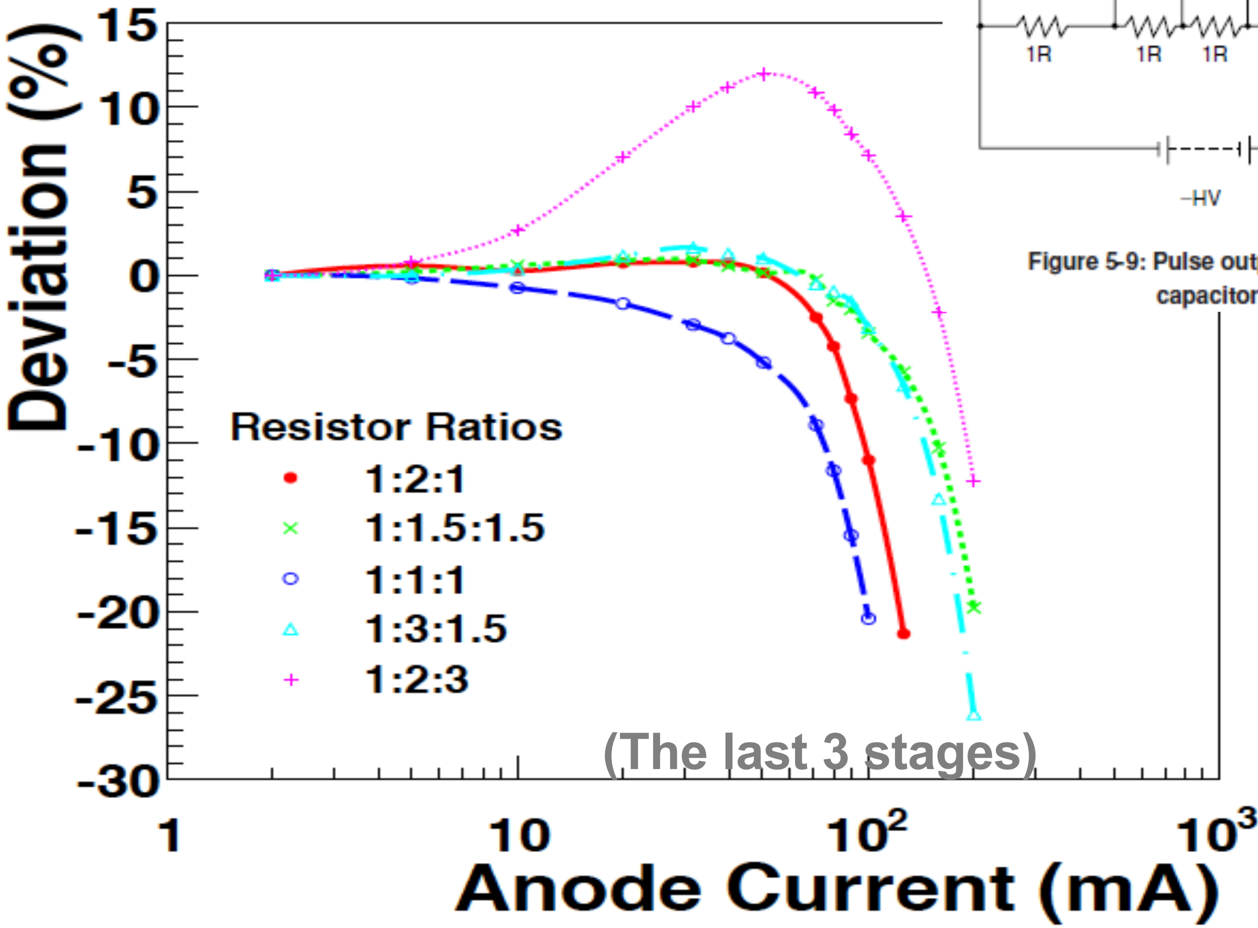


PMT output / peak current (mA)

Non Linearity is the effect of the space charge mainly between the last and the second last dynode.

Space charge. At high currents, space charge can influence the electron trajectories, causing collection losses; at still higher currents it can cause some electrons to return to the surfaces from which they originate

Optimization of Anode Pulse Linearity



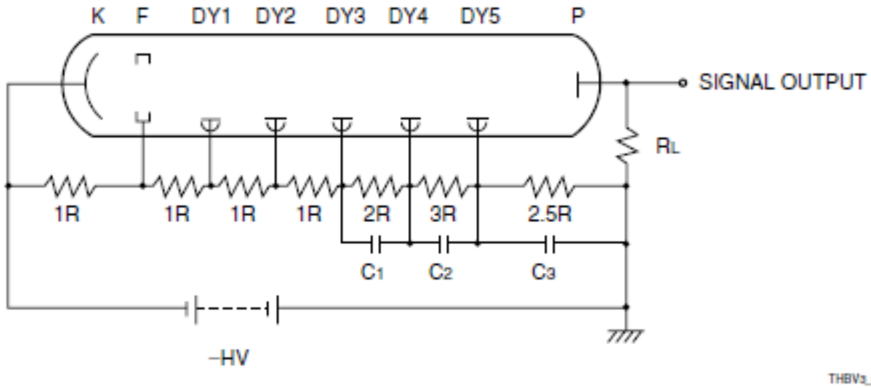
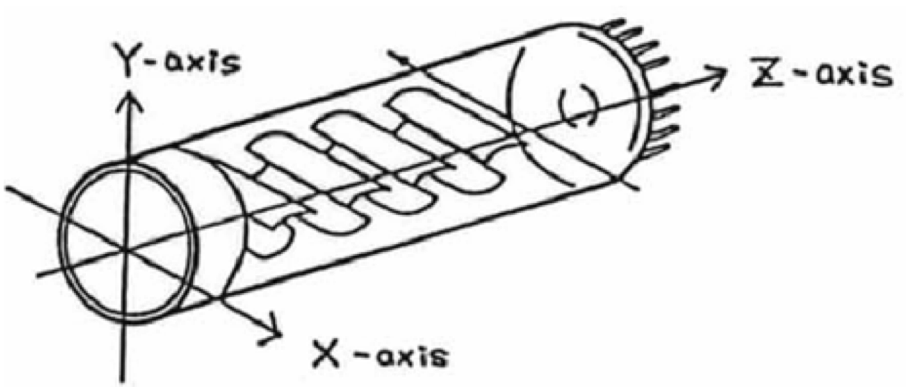
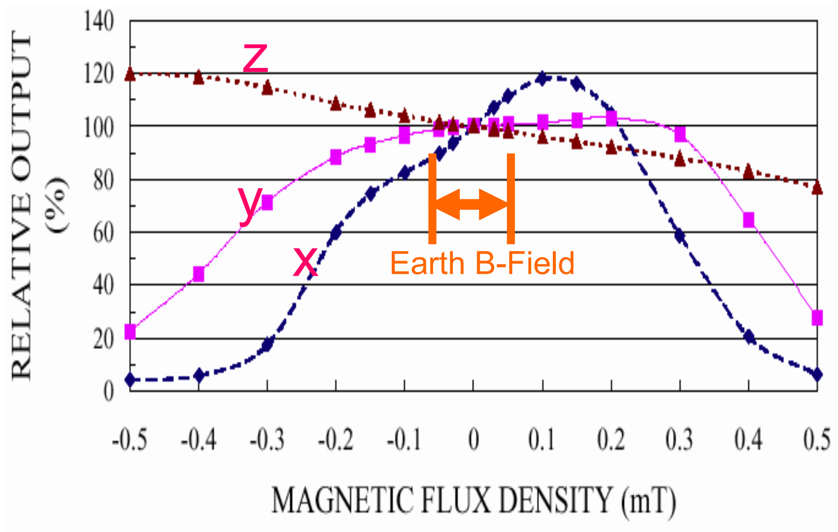
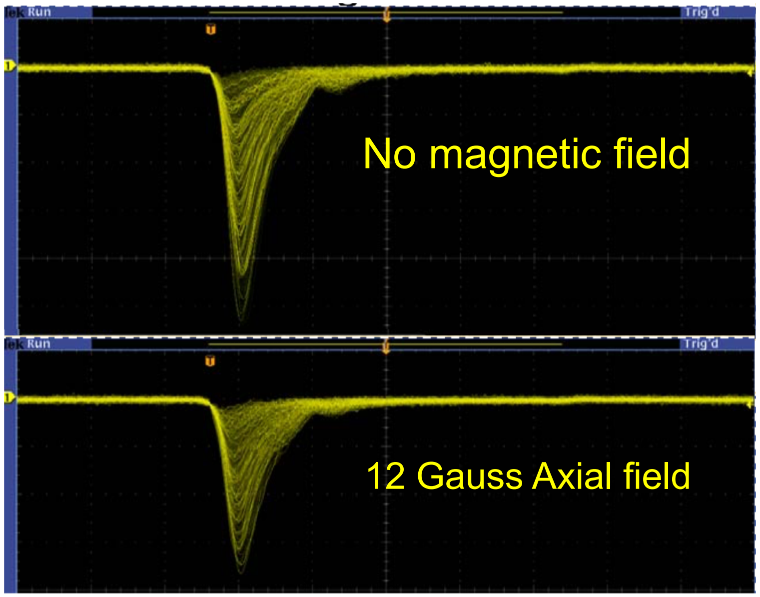


Figure 5-9: Pulse output linearity countermeasures using decoupling capacitors and tapered voltage-divider circuit

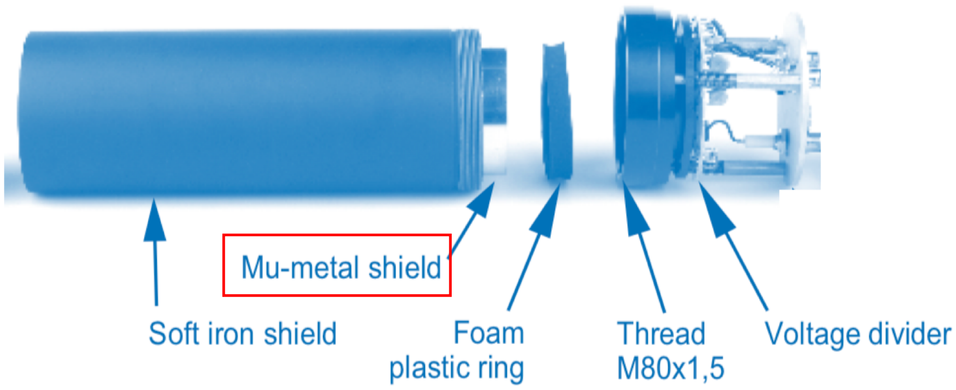
Effect of Magnetic Field on Liner-focus PMT





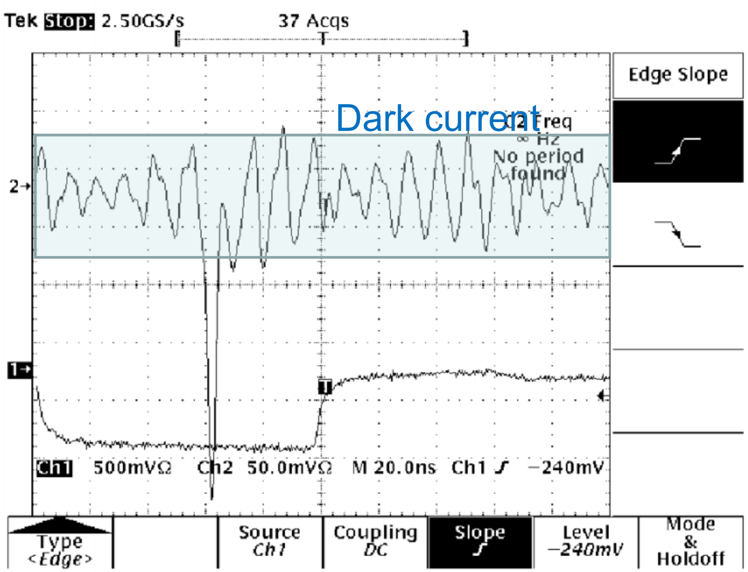


Magnetic Shields

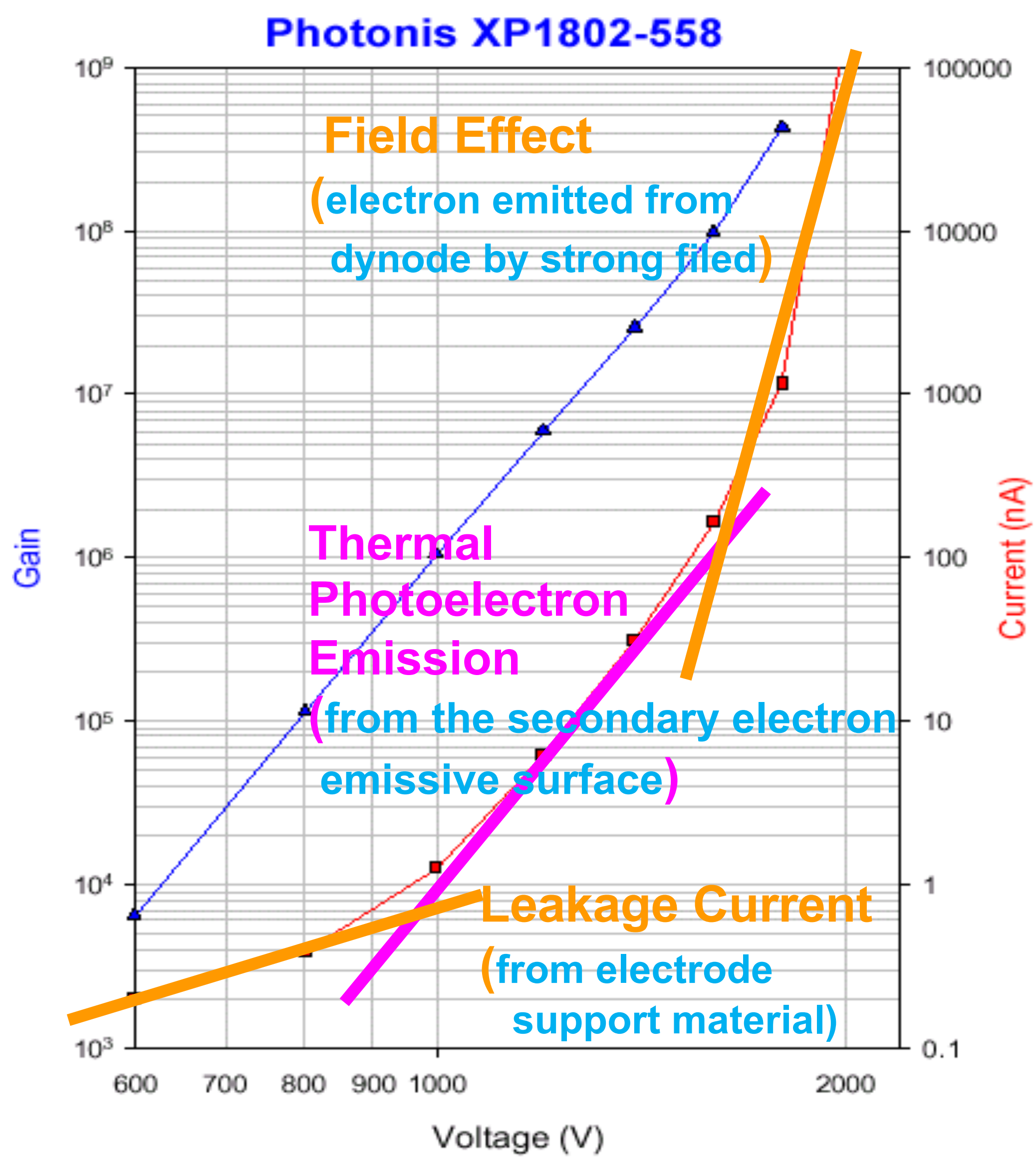


Dark Current

Current without light in



Gain and Dark Current vs. HV



Temperature characteristics

The PMT is more susceptible to ambient temperature than ordinary electronic components. Therefore in precision measurement, the PMT must be operated with temperature control or comparative photometric techniques so that the effects of ambient temperature are minimized.

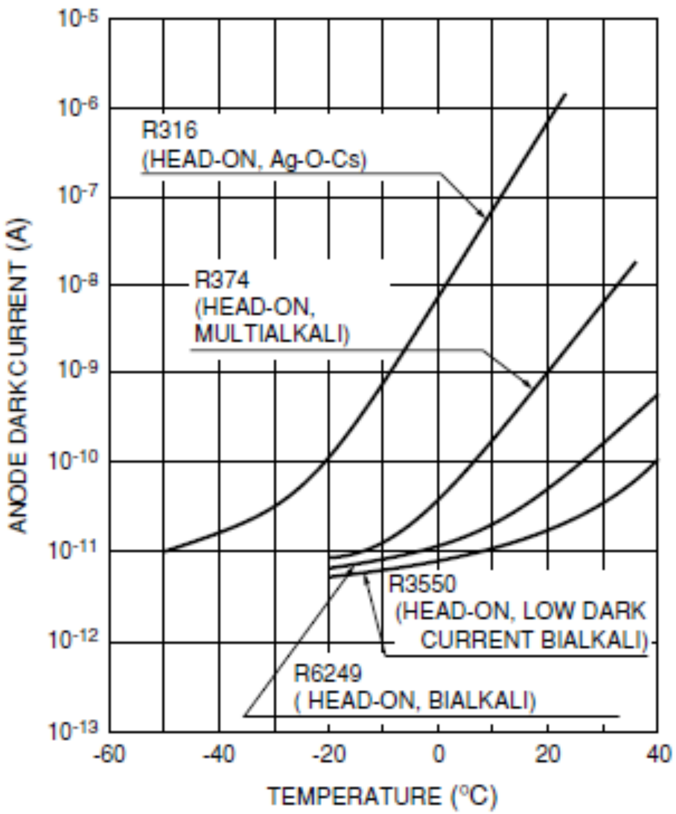


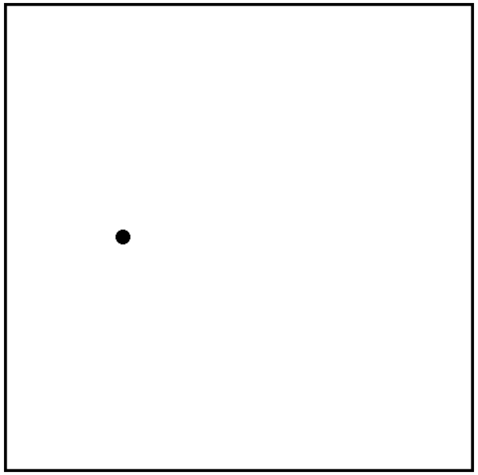
Figure 4-39: Temperature characteristics of anode dark current

- When performing temperature control, note that interior of a PMT is a vacuum and that heat conducts through it very slowly.
- The PMT should be left for one hour or longer until the PMT reaches the same level as the ambient temperature and its characteristics become stable.

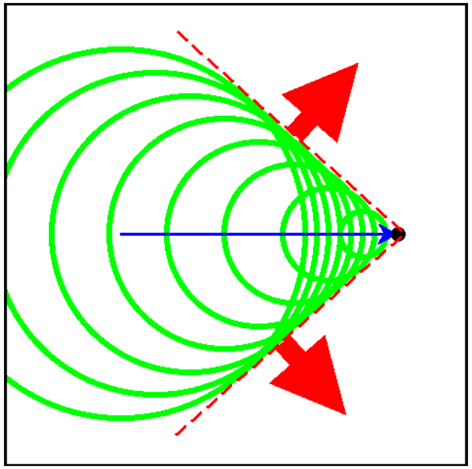
Cerenkov Light

The Cerenkov effect occurs when the velocity of a charged particle traveling through a dielectric medium exceeds the speed of light in the medium.

Index of refraction (n) = (speed of light in vacuum)/(speed of light in medium)

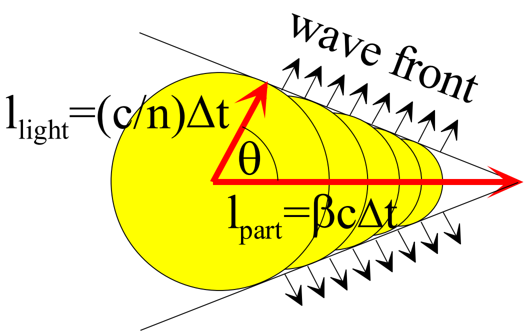


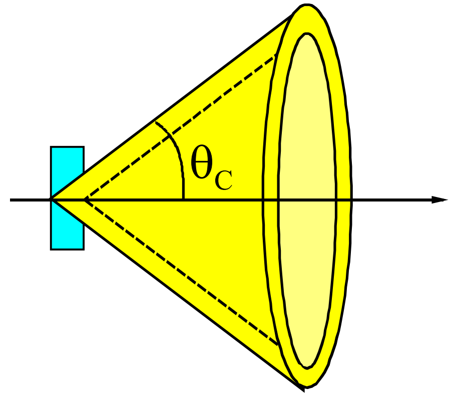
slow

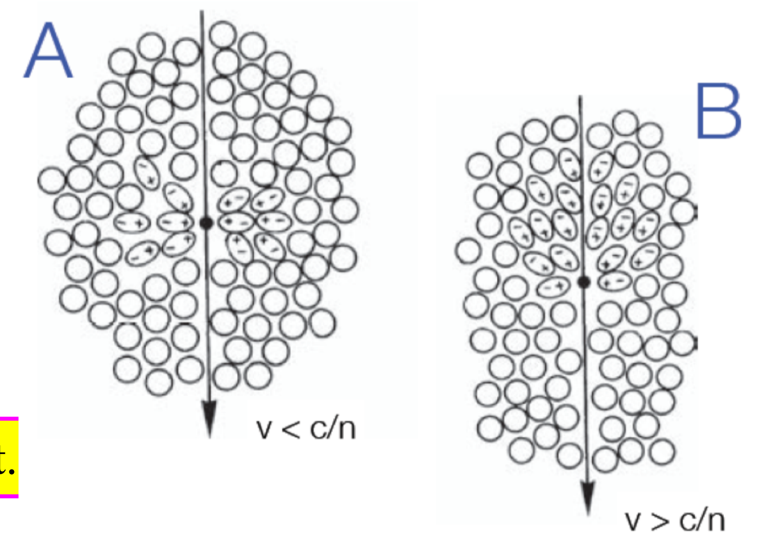


fast

- A charged particles passing through matter will polarize some atomic electrons.
- If the particle exceeds the speed of light c/n then an electromagnetic shock wave will be formed.
- First observed by Pavel Cherenkov in 1934.







In a time *t* wavefront moves (c/n)t but particle moves βct.

A: v < c/n

Induced dipoles symmetrically arranged around particle path; no net dipole moment; no Cherenkov radiation

B: v > c/n

Symmetry is broken as particle faster the electromagnetic waves; non-vanishing dipole moment; radiation of Cherenkov photons

$$\cos\theta_c = \frac{l_{light}}{l_{part}} = \frac{c}{vn}$$

$$= \frac{1}{\beta n} \Rightarrow \beta \geq 1/n$$

$$\beta_{thr} = \frac{1}{n} \rightarrow \theta_C \approx 0$$

Threshold of beta

$$v_{thr} \geq c/n$$

$$\theta_{\max} = \arccos\frac{1}{n}$$

'saturated' angle (β=1)

medium	n	θ_{max} (β=1)	N_{ph} (eV^{-1} cm^{-1})
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

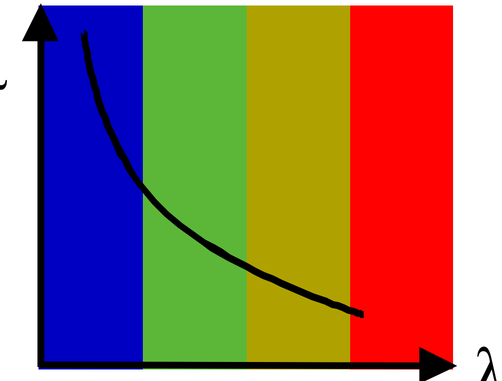
- Energy loss by Cherenkov radiation small compared to ionization (≈0.1%)

typical photon energy:	$\simeq 3$ eV
in water	$\left.\frac{dE}{dx}\right\vert_{cher} = 0.5$ keV/cm $= 0.5$ keV/g/cm^2
cf. ionization	$\left.\frac{dE}{dx}\right\vert_{ion} \geq 2$ MeV/g/cm^2

- Cherenkov effect is a very weak light source

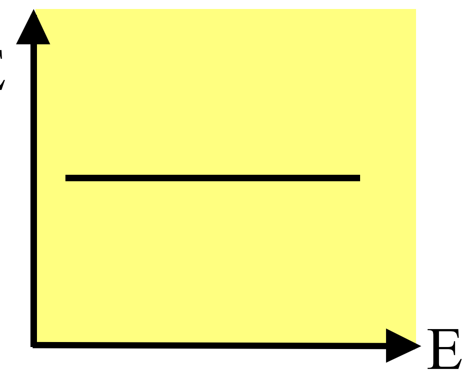
→ need highly sensitive photodetectors

Number of emitted photons per unit length and unit wavelength interval

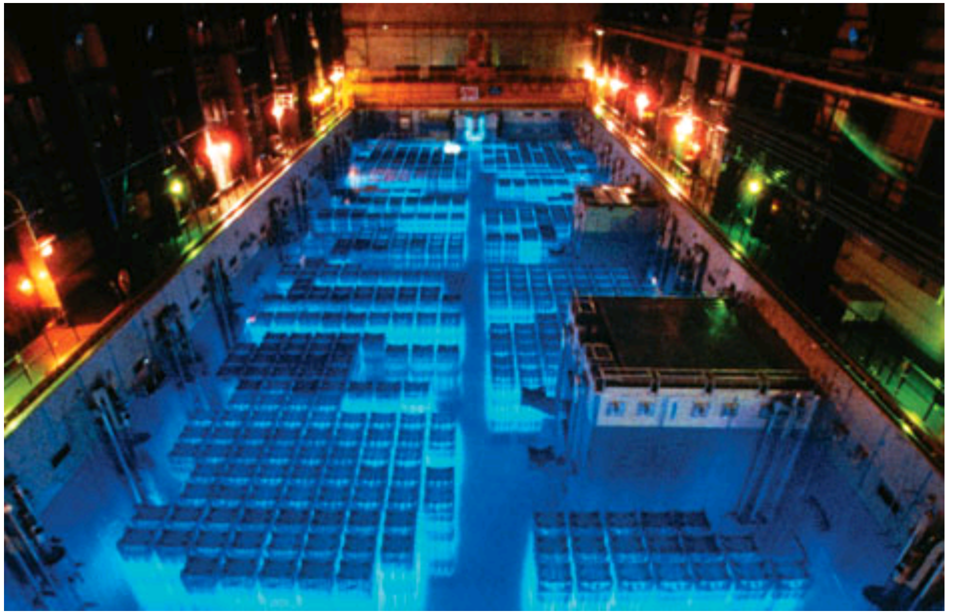


$$\frac{d^2N}{dxd\lambda} = \frac{2\pi z^2\alpha}{\lambda^2}\left(1-\frac{1}{\beta^2 n^2}\right) = \frac{2\pi z^2\alpha}{\lambda^2}\sin^2\theta_C$$

$$\frac{d^2N}{dxd\lambda} \propto \frac{1}{\lambda^2} \quad \text{with } \lambda = \frac{c}{\nu} = \frac{hc}{E} \quad \frac{d^2N}{dxdE} = const.$$



- More photons are produced at short wavelengths.
- Enhanced visible light at the blue end of the spectrum.
  - Characteristic glow from a reactor



"We had an especial joy in observing that our products containing concentrated radium were all spontaneously luminous."

Our precious products, for which we had no shelter, were arranged on tables tables and boards; from all sides we could see their slightly luminous and boards; from all sides we could see their slightly luminous silhouettes, and all these gleamings, which seemed suspended in the darkness, stirred us with ever new emotion and enchantment."

Marie Curie, 1899 Paris

The Nobel Prize in Physics 1958

"for the discovery and the interpretation of the Cherenkov effect"

Pavel Alekseyevich Cherenkov

1/3 of the prize

USSR

P.N. Lebedev Physical Institute Moscow, USSR

b. 1904
d. 1990

Il´ja Mikhailovich Frank

1/3 of the prize

USSR

University of Moscow; P.N. Lebedev Physical Institute Moscow, USSR

b. 1908
d. 1990

Igor Yevgenyevich Tamm

1/3 of the prize

USSR

University of Moscow; P.N. Lebedev Physical Institute Moscow, USSR

b. 1895
d. 1971

Types of Cerenkov Counters

Cerenkov counters are used to identify particles.

Threshold counter

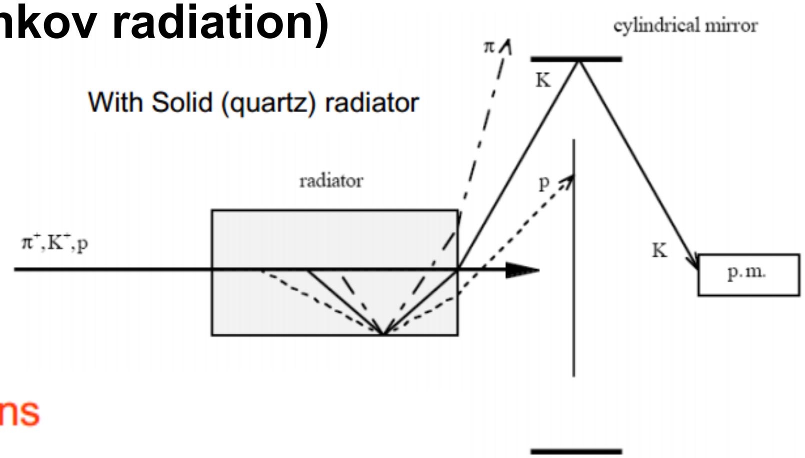
(on/off device)

Differential counter

(makes use of the angle of the Cerenkov radiation)

Ring imaging counter

(makes use of the “cone” of light)



Components of a Cherenkov Detector

- Radiator : To produce photons
- Mirror/lens etc. : To help with the transport of photons
- Photodetector : To detect the photons

➢ Typically, in Accelerator based experiments, Momentum (p) is measured by a Magnetic Spectrometer : Tracking detectors and a Magnet.

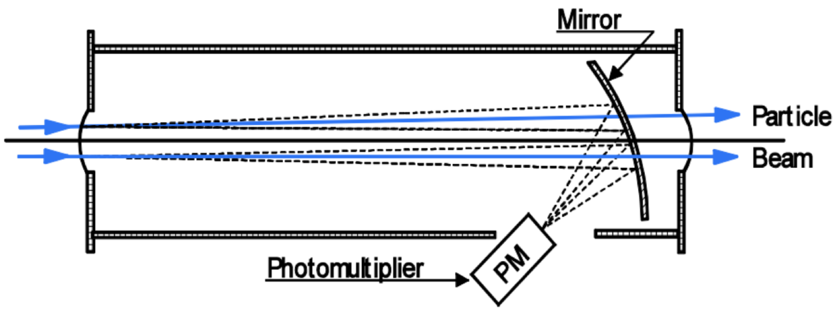
Each of the above counter is designed to work in a certain momentum range.

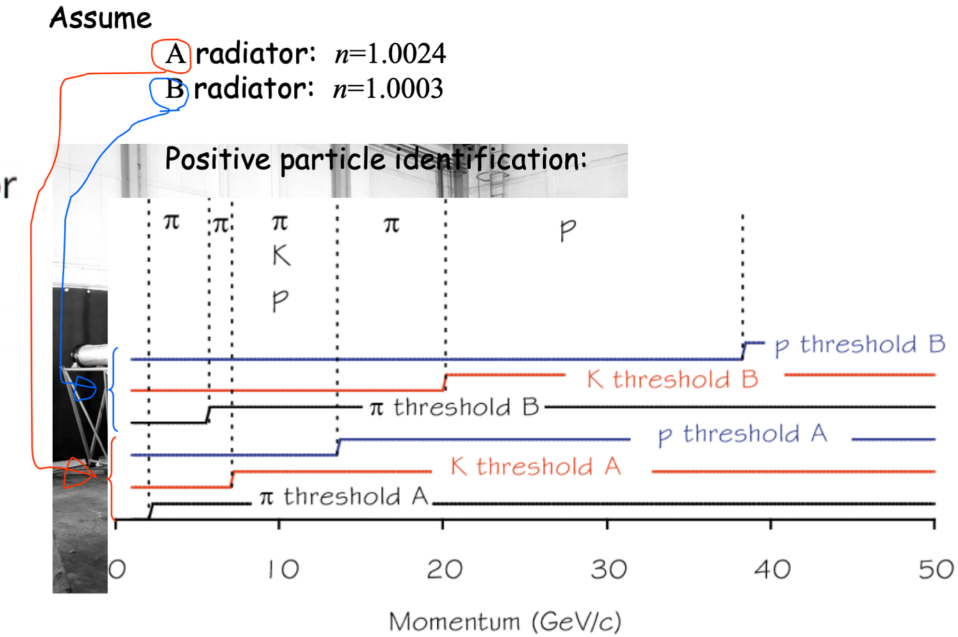
Threshold counter

$$\beta_t = \frac{1}{n}$$

For a counter filled with material of index of refraction n, the *threshold* momentum, p_t, for a particle with mass, m, is given by

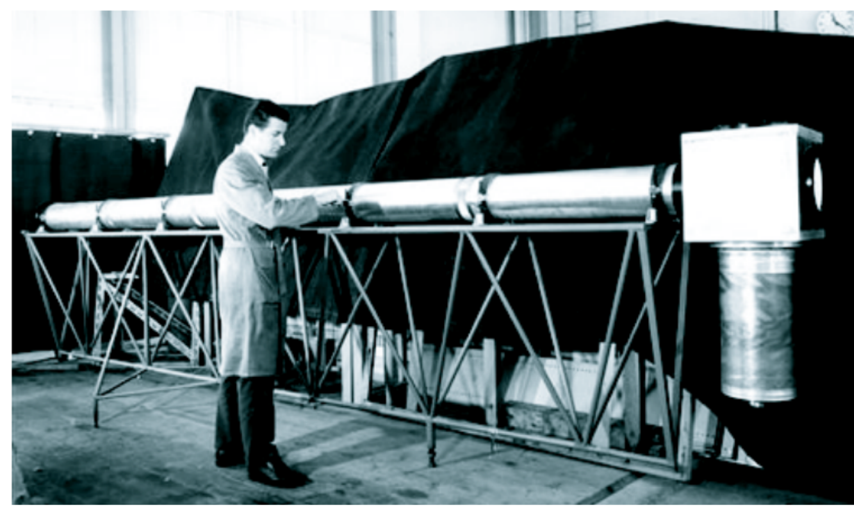
$$p_t = m\gamma_t\beta_t c = \frac{mc}{\sqrt{n^2 - 1}}.$$





- Threshold counters are useful to identify particles in a beam line (with fixed momentum) for example a 30 GeV π beam with some proton contamination

- By choosing a medium with a suitable refractive index, it can be arranged that the π will produce light, but the protons will not



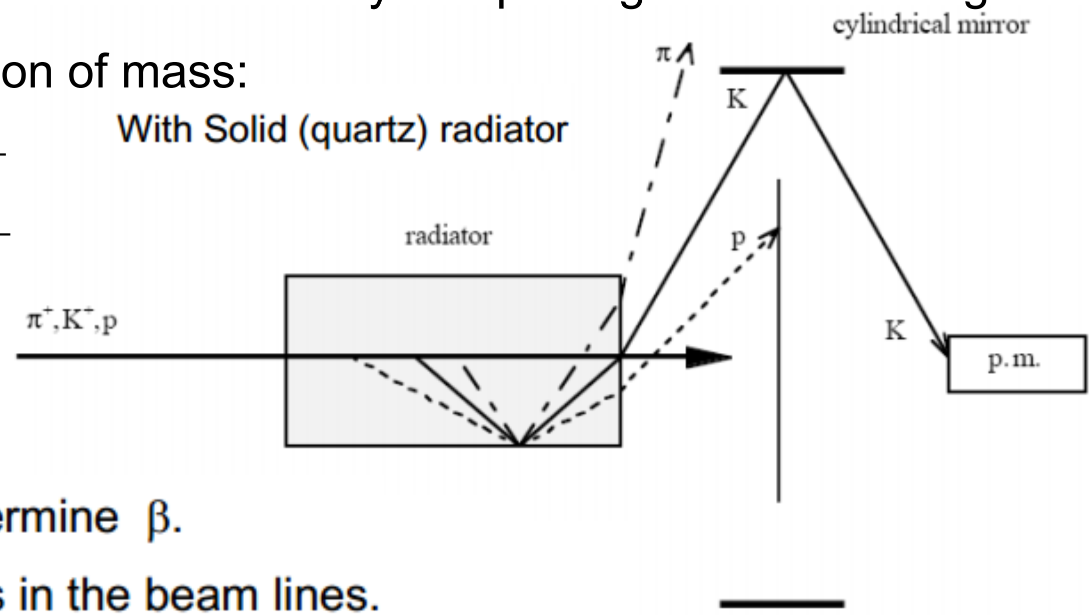
Differential Cerenkov Counter:

Makes use of the angle of Cerenkov radiation and only samples light at certain angles.

For fixed momentum cosθ is a function of mass:

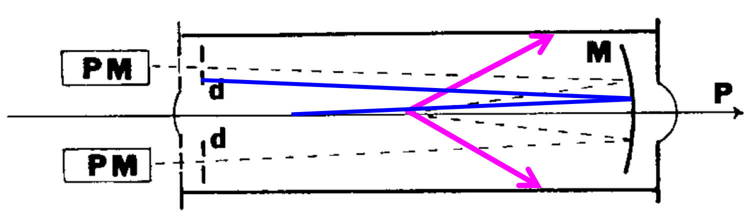
$$\cos\theta = \frac{1}{n\beta} = \frac{1}{n(p/E)} = \frac{\sqrt{m^2 + p^2}}{np}$$

With Solid (quartz) radiator



- From the Cherenkov angle (θ) determine β.
- Mostly used for identifying particles in the beam lines.

Differential cerenkov counters typically on work over a fixed momentum range (good for beam monitors, e.g. measure π or K content of beam).



Not all light will make it to phototube

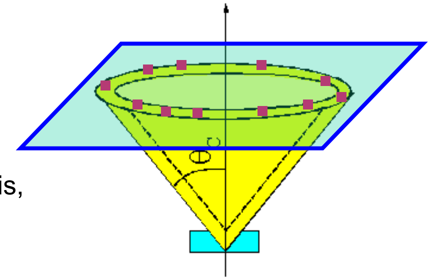
Ring Imaging Cherenkov detectors (RICH)

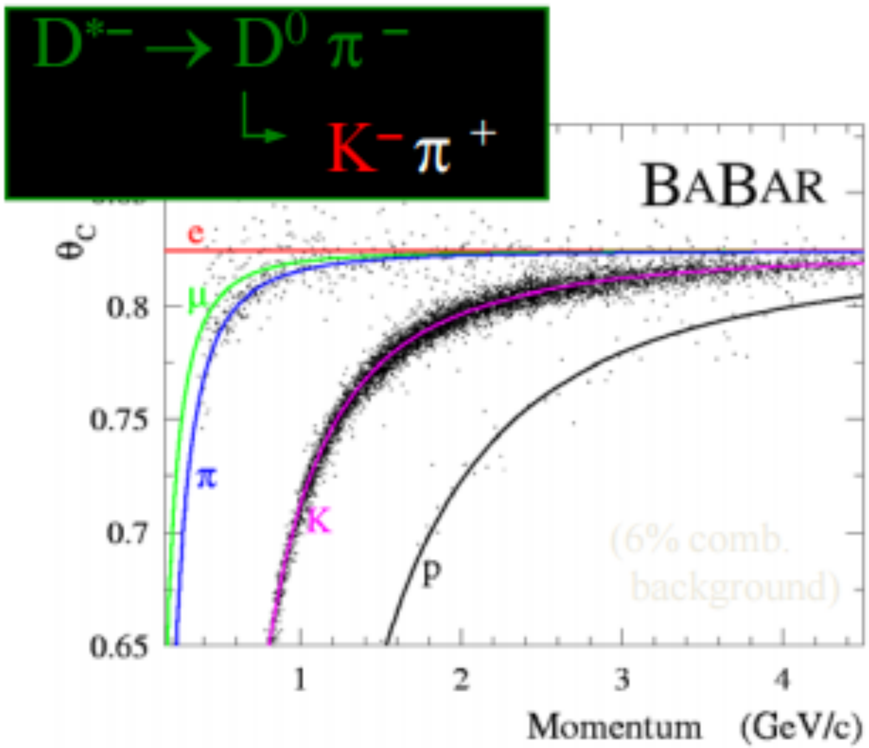
RICH detectors determine θ_C by intersecting the Cherenkov cone with a photosensitive plane

→ requires large area photosensitive detectors, e.g.

- wire chambers with photosensitive detector gas
- PMT arrays

(J. Seguinot, T. Ypsilantis, NIM 142 (1977) 377)





$$\theta_C = \arccos\left(\frac{1}{n\beta}\right) = \arccos\left(\frac{1}{n}\cdot\frac{E}{p}\right)$$

$$= \arccos\left(\frac{1}{n}\cdot\frac{\sqrt{p^2+m^2}}{p}\right)$$

$$\cos\theta_C = \frac{1}{n\beta} \quad \rightarrow \quad \frac{\sigma_\beta}{\beta} = \tan\theta\cdot\sigma_\theta$$

Detect $N_{p.e.}$ photons (photoelectrons) →

$$\sigma_\theta \approx \frac{\sigma_\theta^{p.e.}}{\sqrt{N_{p.e.}}}$$

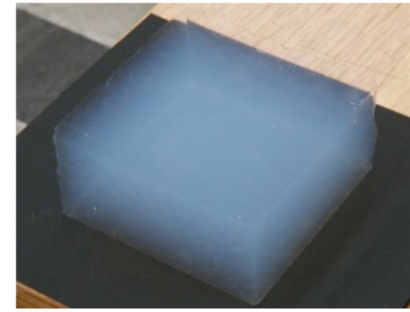
→ minimize $\sigma_\theta^{p.e.}$

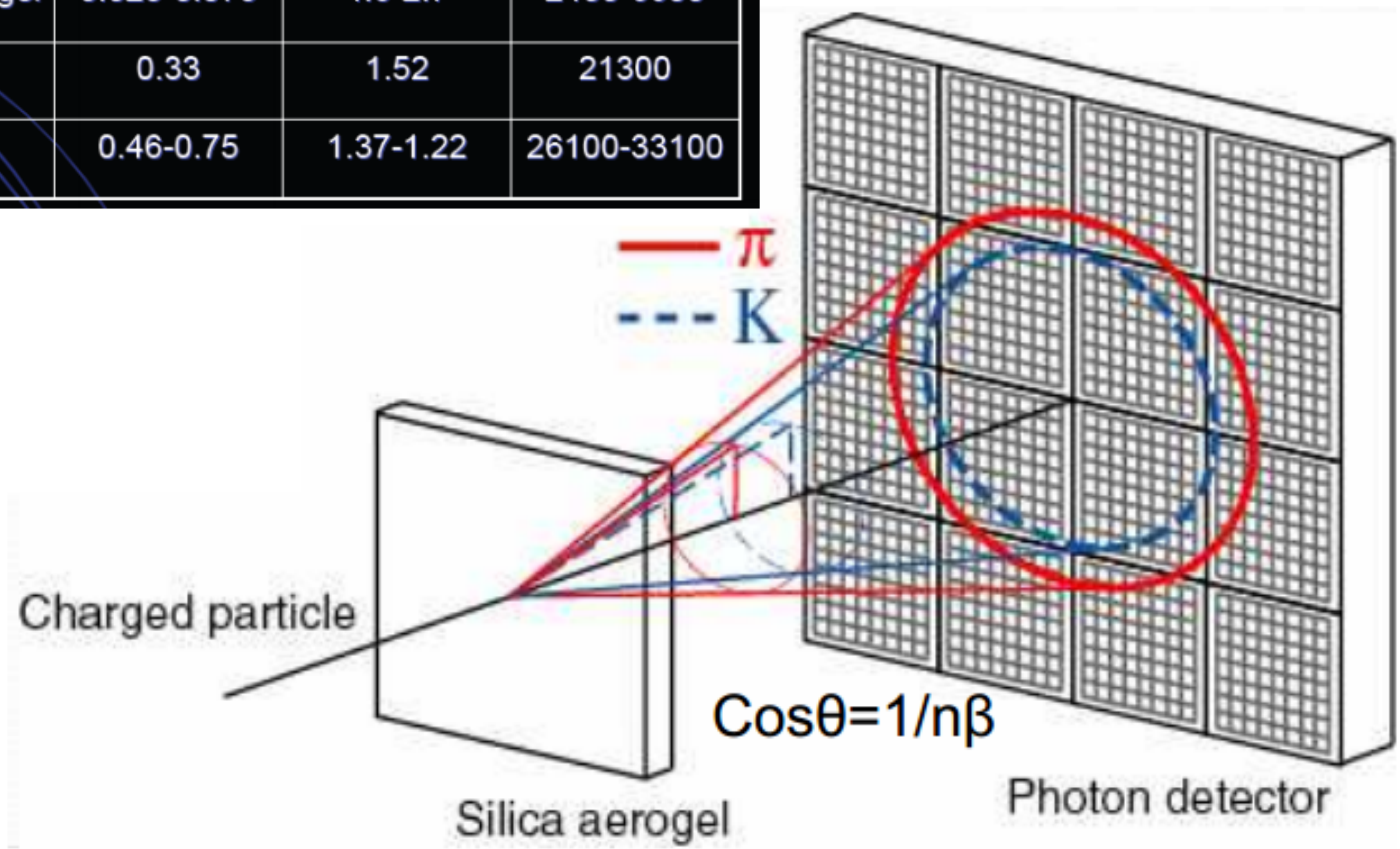
→ maximize $N_{p.e.}$

Example of radiators

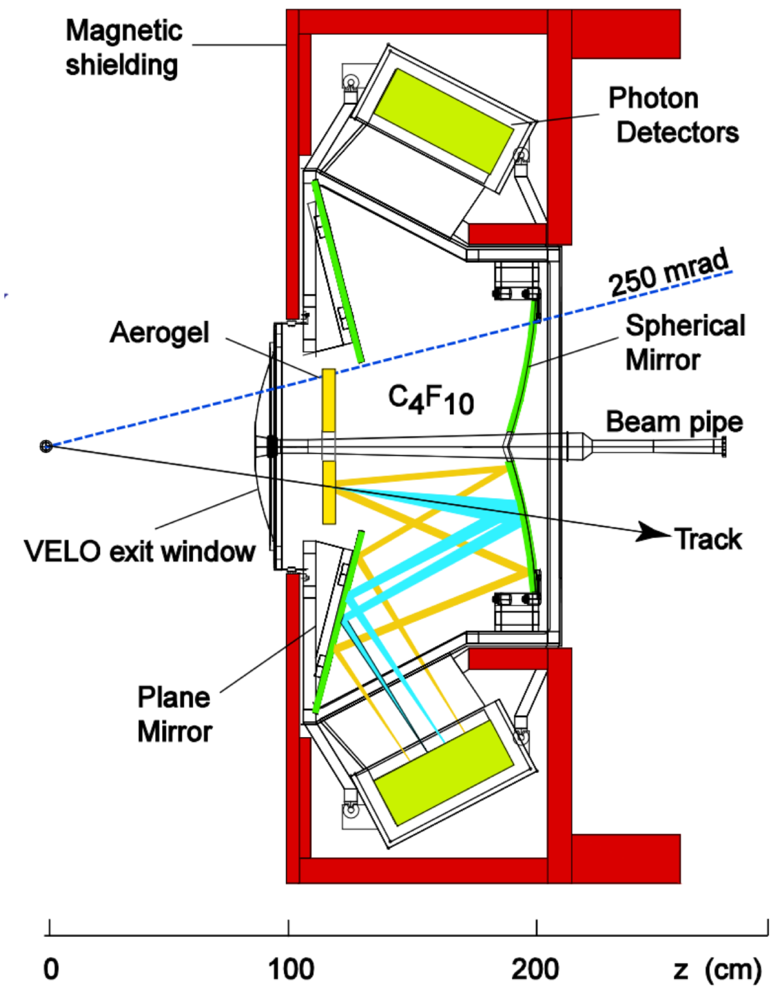
Medium	n-1	γ_{th}	Photons/m
He (STP)	3.5 10^{-5}	120	3
CO_2 (STP)	4.1 10^{-4}	35	40
Silica aerogel	0.025-0.075	4.6-2.7	2400-6600
water	0.33	1.52	21300
Glass	0.46-0.75	1.37-1.22	26100-33100

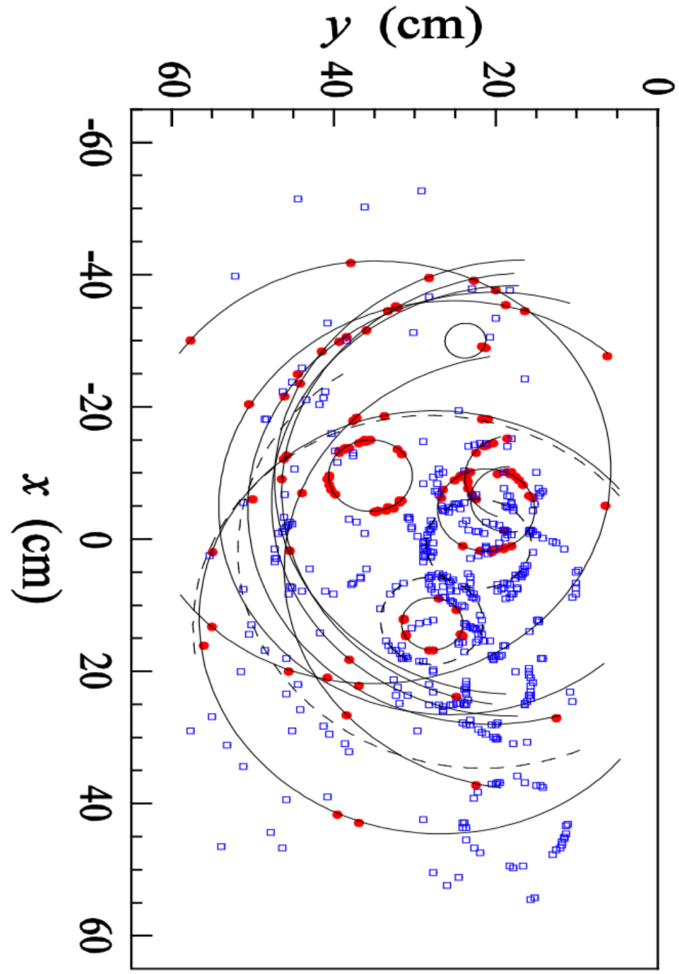
Aerogel: network of SiO_2 nano-crystals





- Cross-section through RICH-1 of LHCb
- Makes use of two separate radiators: C4F10 gas and silica aerogel (a solid) A second (flat) mirror is used to limit the size of the detector along the beam axis





Simulated event in RICH-1

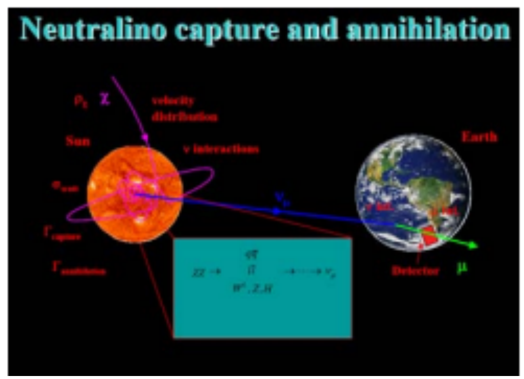
Large rings: aerogel, small: C_4F_{10}

Cherenkov Detectors in Astro Particle Physics

Goal: Contribute to the understanding of our Universe.

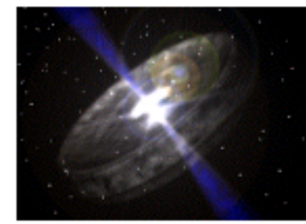
- **Understanding production mechanism ('cosmic accelerators') of HE cosmic rays ;**
- **Study very energetic galactic / extragalactic objects : SN remnants, microquasars, GRB, AGN,...;**
- **Search for Dark matter (wimps)**
- **. . .**

Micro-quasars

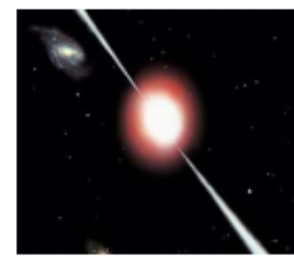


SNR

AGN



GRB



Neutrinos: Advantages:

- Neutral : Hence Weak interaction only
- Neutrinos point back to the astrophysical production source
  - Unlike photons which interact with CMB and matter…
  - or protons: which also undergo deflection by magnetic fields

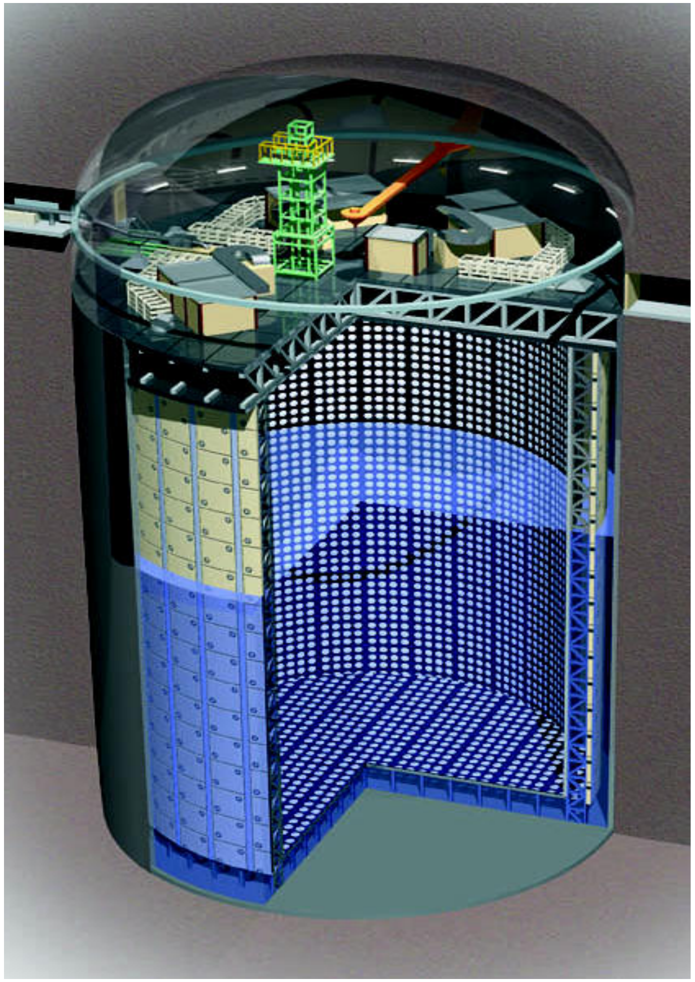
Disadvantages:

- Rate of arrival very low. Hence need very large detectors.
- Using the Ocean , ice in Antartica etc.

Large water volume neutrino detectors

Examples:

- SNO
- Super-Kamiokande
  50 k ton H_20
  1 km underground

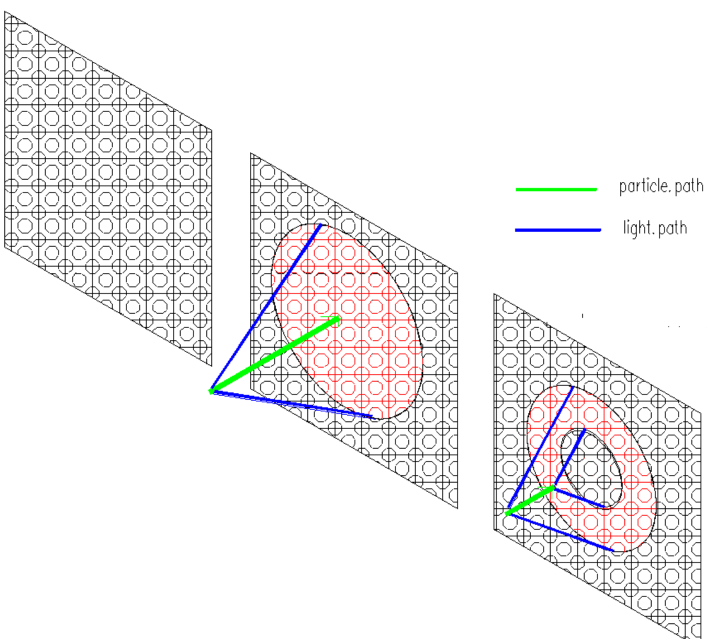


Cherenkov rings are an ideal technique for detecting $\nu \rightarrow \mu$, e

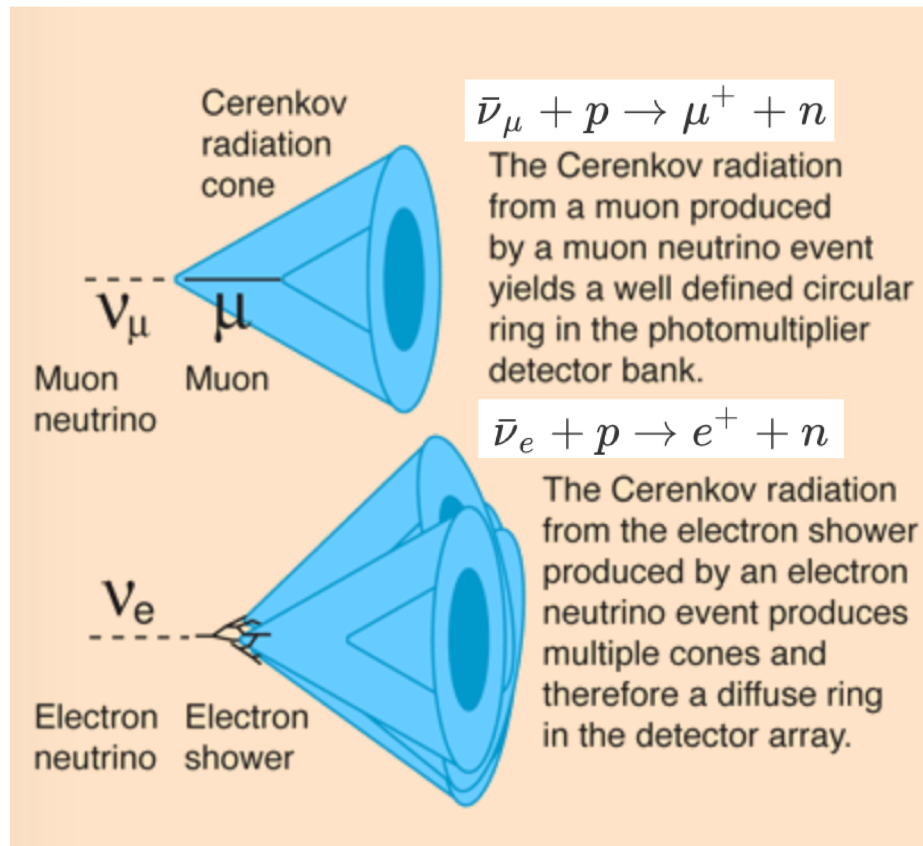
Ring Imaging

Cherenkov imaging is used in neutrino detectors.

- Muons from μ-neutrinos make a clean ring.
  - high dE/dx compared to electron, short range.
- Electrons from *e*-neutrinos make a diffuse ring.
  - Electrons interact and shower

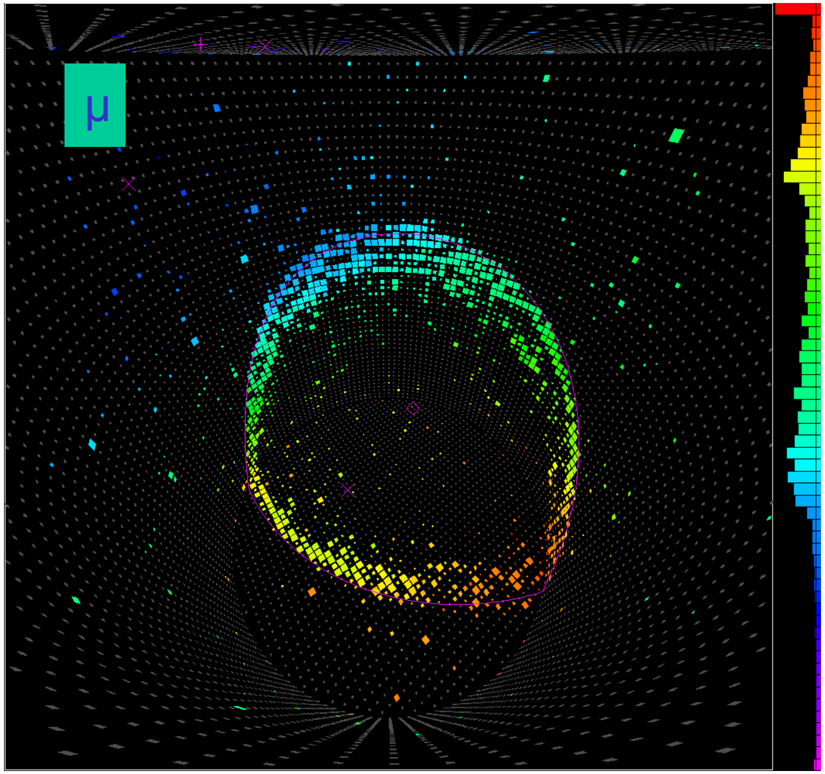


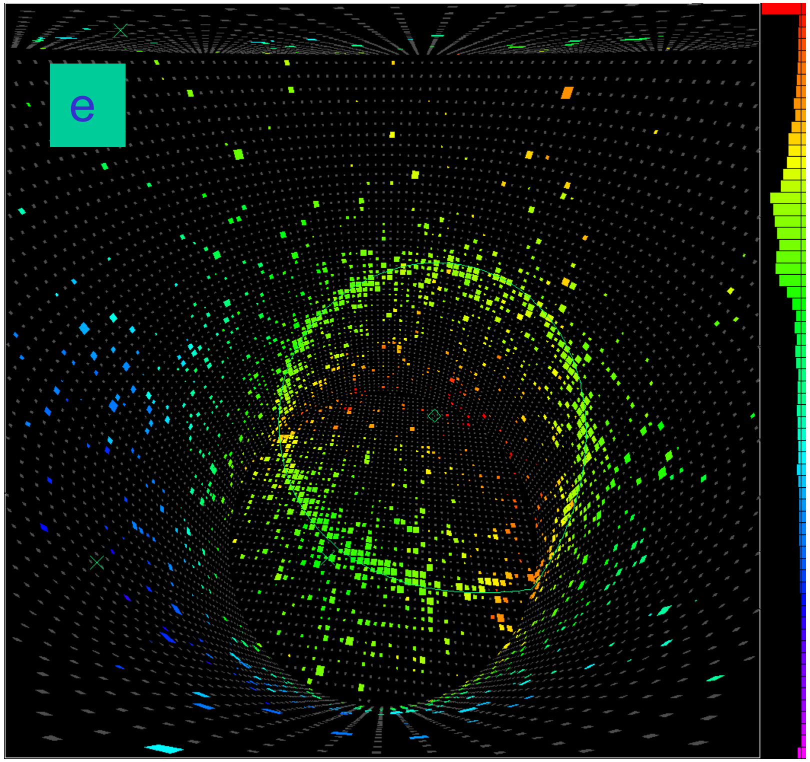
- A particle with velocity v creates light at a fixed angle.



Cherenkov Rings in Super-K

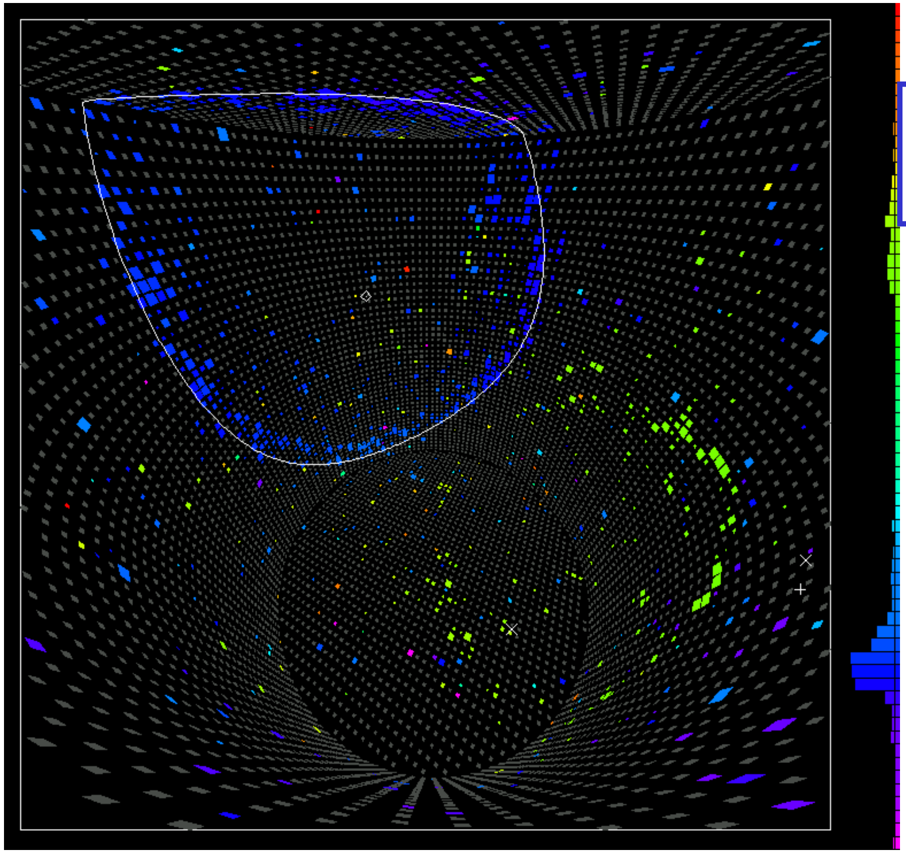
Cherenkov light a perfect signature of a neutrino interaction in water.





No momentum measurement, so PID performed from sharpness of ring.
Timing response of PMTs necessary to determine particle direction.

SuperK is a water RICH.



For water n=1.33

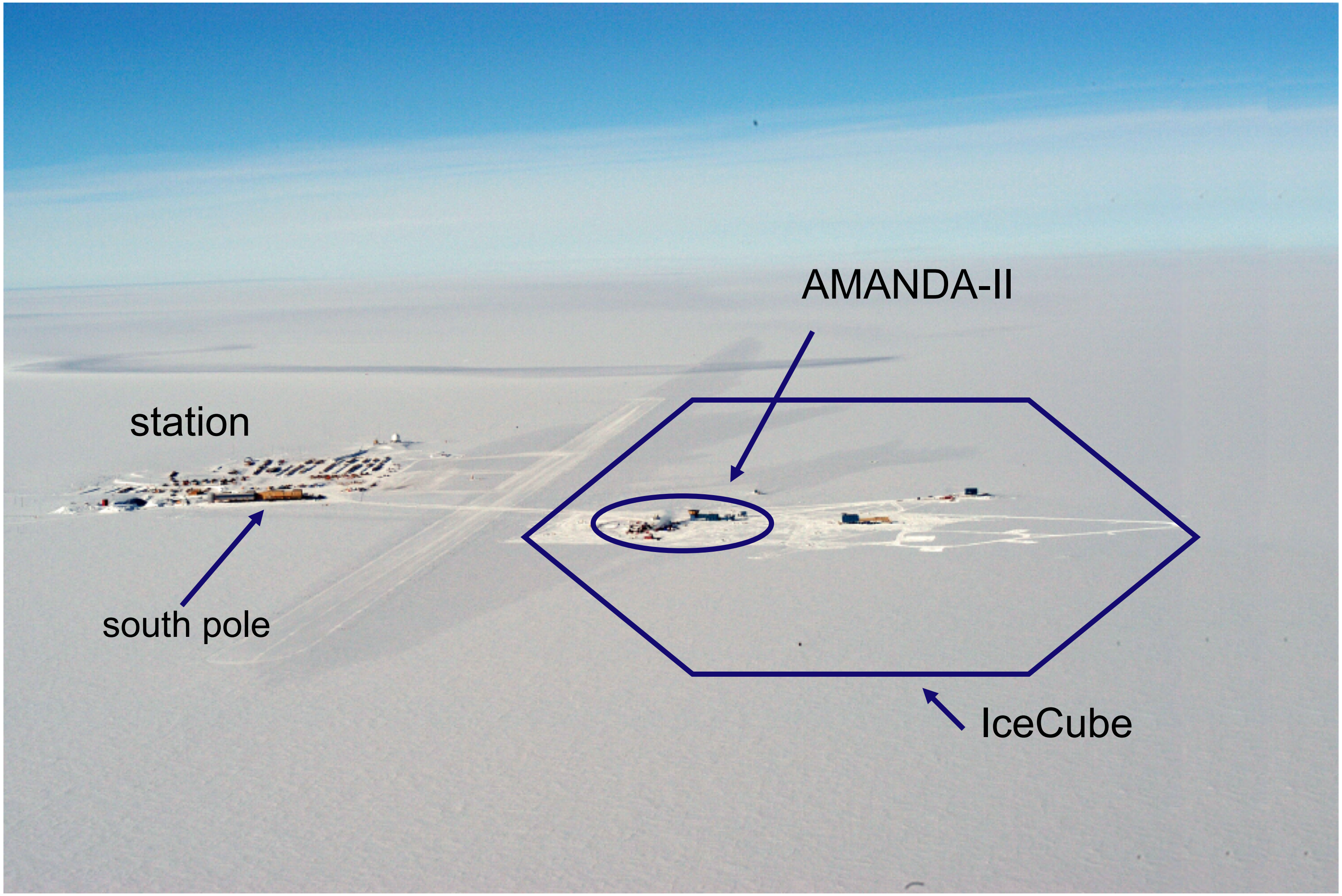
For β=1 particle $\cos\theta = 1/1.33$, $\theta = 41^{o}$

SuperK has: 50 ktons of H_2O

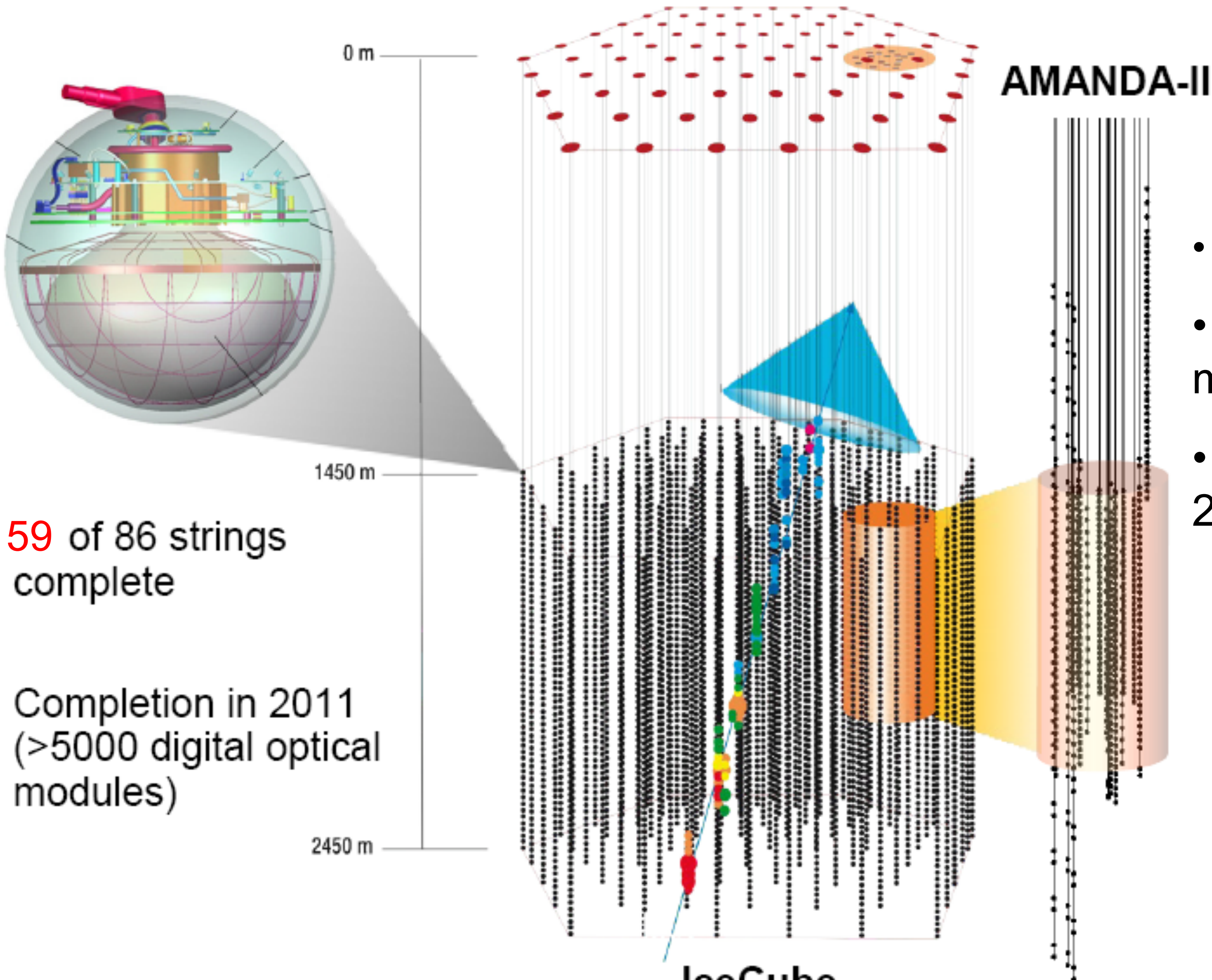
Inner PMTS: 1748 (top and bottom) and 7650 (barrel)

outer PMTs: 302 (top), 308 (bottom) and 1275(barrel)

Antarctic Physics



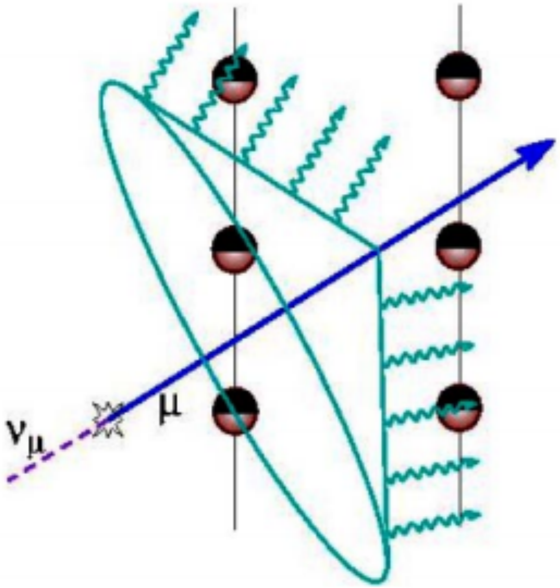
Neutrino Detectors

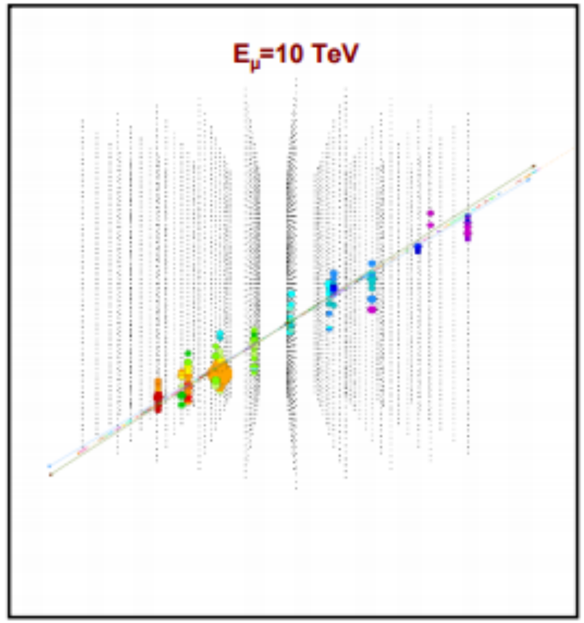


- 59 of 86 strings complete
- Completion in 2011 (>5000 digital optical modules)

- 19 strings
- 677 optical modules
- Operated 2000-2009

Ice Cube/AMANDA Event signatures

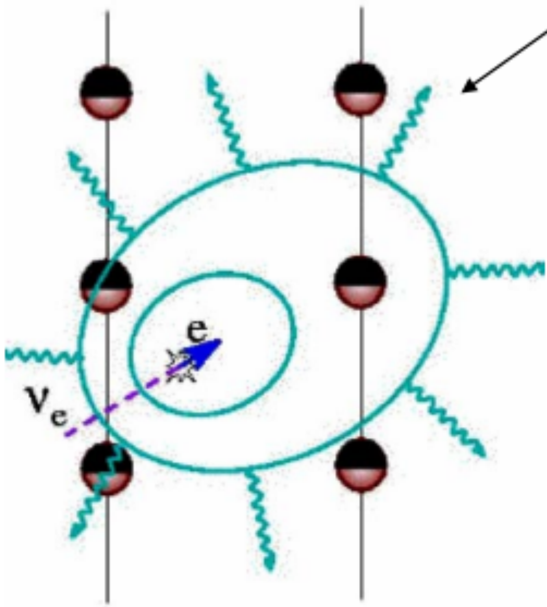


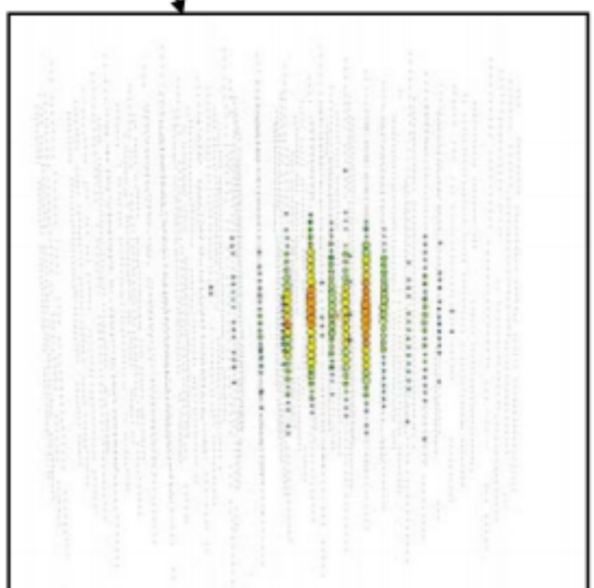


ν_μ from CC interactions

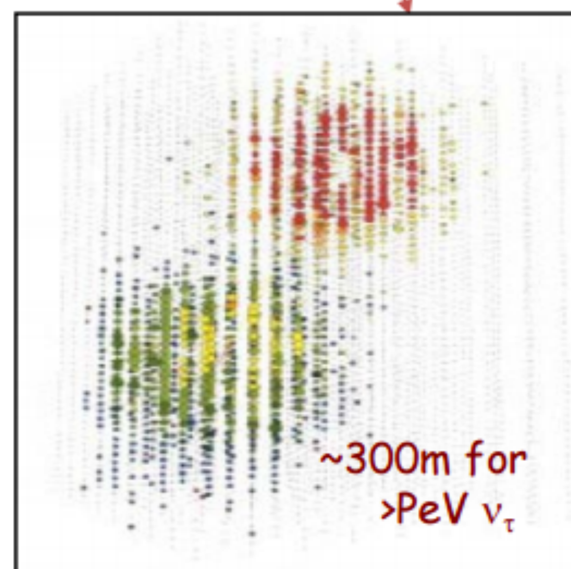
All signals from Cherenkov Radiation.

ν_e from CC or ν_x from NC interactions





$\nu_\tau \rightarrow \tau \rightarrow \mu$



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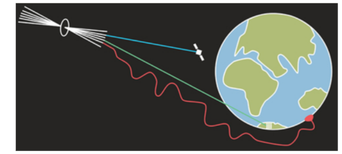
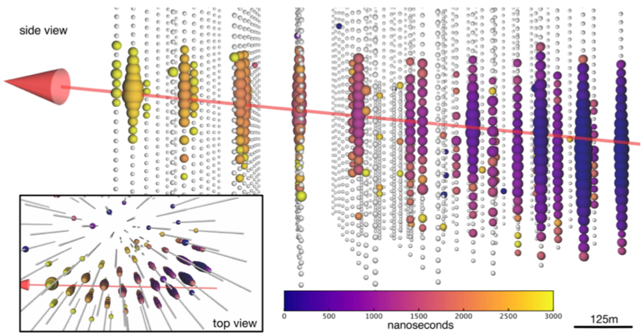
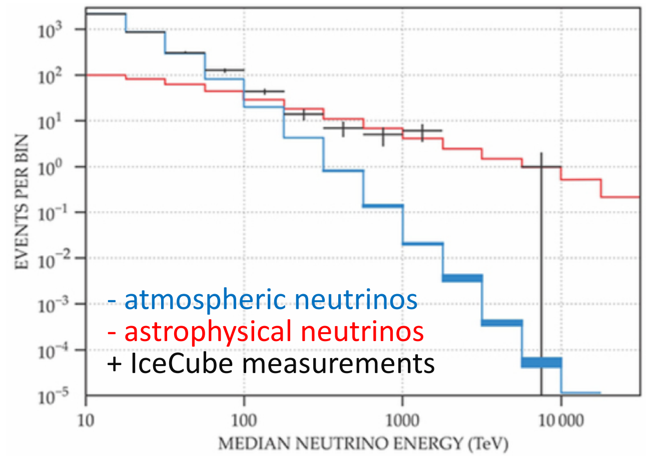
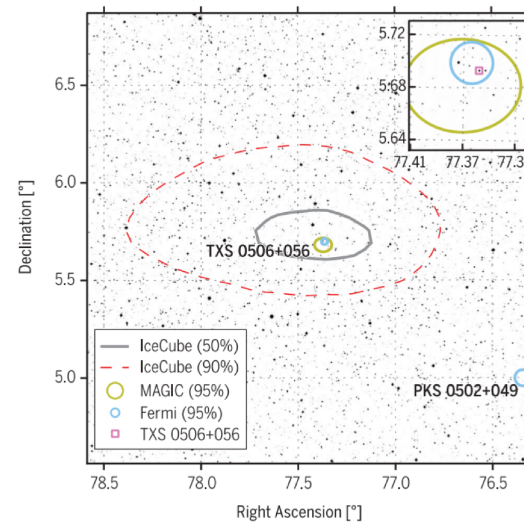


Astrophysical high-energy neutrinos

News from multiple messengers—neutrinos, cosmic rays, and photons—provides clues to the cosmic sources that create some of the most energetic particles observed on Earth.







Multimessenger observations of blazar TXS 0506+056.

The figure shows the event that pointed to TXS 0506+056, observed by IceCube on 22 September 2017. The colored circles indicate the firings of Cherenkov detectors; purple detectors fired first, yellow detectors three microseconds later. The straight line shows the reconstructed muon path. The IceCube collaboration estimates that the neutrino triggering the event had an energy of about 300 TeV.

https://physicstoday.scitation.org/do/10.1063/PT.6.1.20180712a/full/

https://physicstoday.scitation.org/doi/10.1063/PT.3.4043