Scintillation Detectors

22.104 Spring 2002

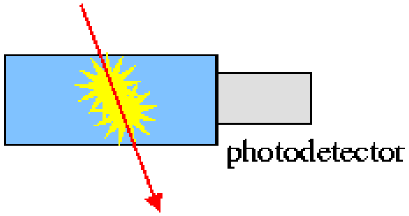
General Issues

- Sensitivity
- Detector Response
- Energy Resolution
- Response Function
- Response Time
- Detector Efficiency
- Dead Time

Basic Concept

- Radiation interacts in material
- Energy converted to photons
- Photons collected by photodetector
- Photodetector produces electrical signal

Scintillation Detector



Energy deposition by ionizing particle
→ production of scintillation light (luminescense)

Scintillators are multi purpose detectors

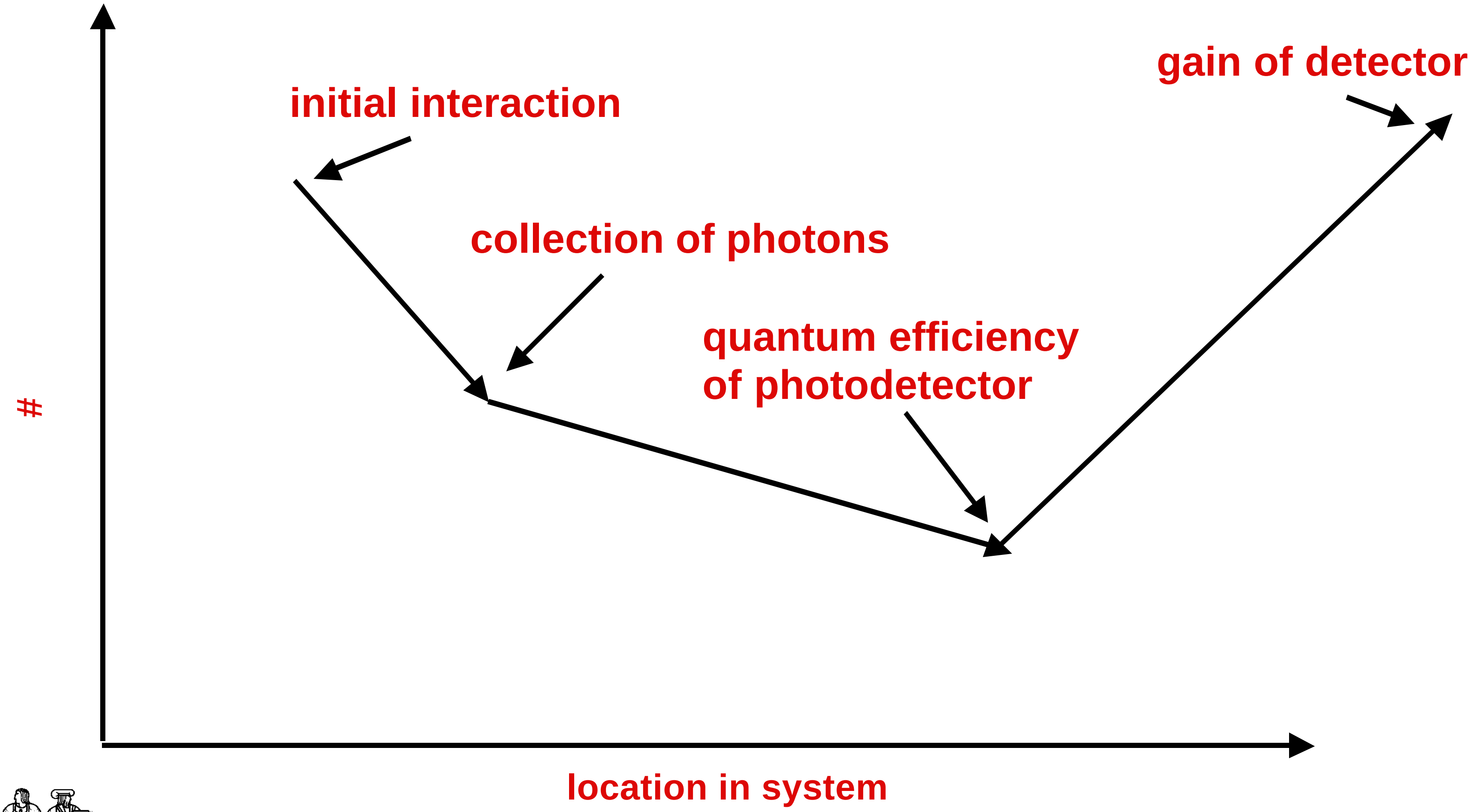
☞ calorimetry
☞ time of flight measurement
☞ tracking detector (fibers)
☞ trigger counter
☞ veto counter
.....

Two material types: Inorganic and organic scintillators

high light output
but slow

lower light output
but fast

Energy resolution and “quantum sinks”



initial interaction

collection of photons

quantum efficiency
of photodetector

gain of detector

#

location in system

Do Statistics Dominate the Resolution?

Location	Number of "Quanta"	Factors
Initial Interaction	Typical efficiency ~ 10 to 15% for scintillators	Energy deposited Conversion efficiency
Geometric Collection Efficiency	Varies with geometry Typical collection efficiency may be ~ 25%	Size of Scintillator Surface finish Index of refraction PMT cathode uniformity **Variations are not statistical**
Quantum Efficiency	Depends on cathode material PMTs around 20% Photodiodes ~ 80%	Spectral response of cathode Uniformity across total area
Detector Gain	PMT ~ 10^5 or more Photodiodes ~ 1 Avalanche PD ~ 100's	Must be large enough to overcome subsequent amplifier electronic noise

Key Properties of Scintillators

- Sensitivity to Energy
- Fast Time Response
- Pulse shape discrimination

Basic Scintillator Materials

- Inorganic phosphors
  - ZnS, GdOS, LaOS
- Inorganic crystals
  - NaI, CsI, CdWO, BGO, BaF, YSO, LSO
- Gases
  - Xe, Ar, Ne
- Glasses
  - Li, B
- Organic liquids and plastics

Other detectors

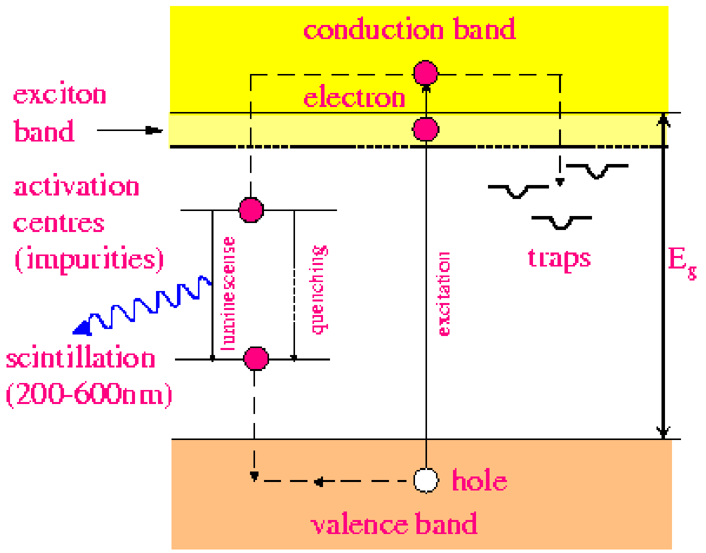
- **Cherenkov light**
  - requires very high velocity charged particles
  - example is β detection
- **Neutron detection**

Steps in scintillation detection process

- radiation interacts with material
- energy transferred to molecular or crystal level
- energy emitted in form of photons
- photons collected by photodetector
- photodetector produces electrical signal
- processed by subsequent electronics

Scintillator Mechanisms

1a. Inorganic crystalline scintillators (NaI, CsI, BaF_2...)



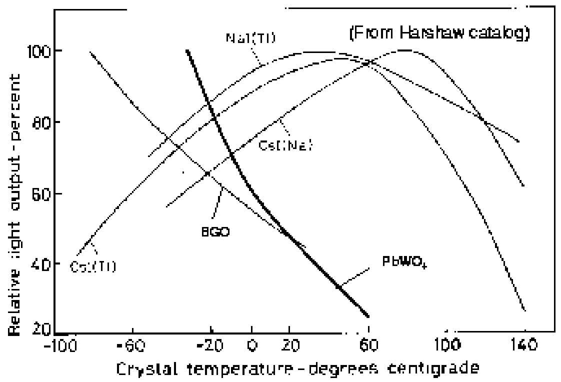
often ≥ 2 time constants:

- fast recombination (ns-μs) from activation centre
- delayed recombination due to trapping (≈ 100 ms)

Due to the high density and high Z inorganic scintillator are well suited for detection of charged particles, but also of γ.

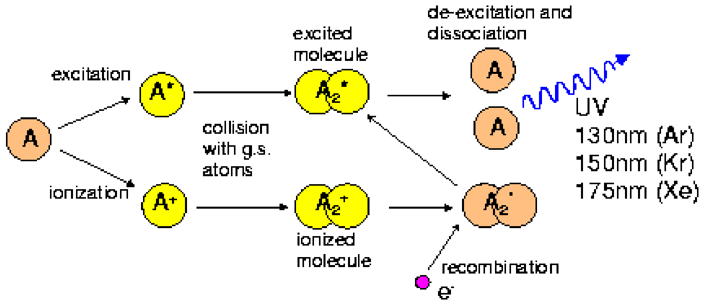
Inorganic Scintillators

Light output of inorganic crystals shows strong temperature dependence



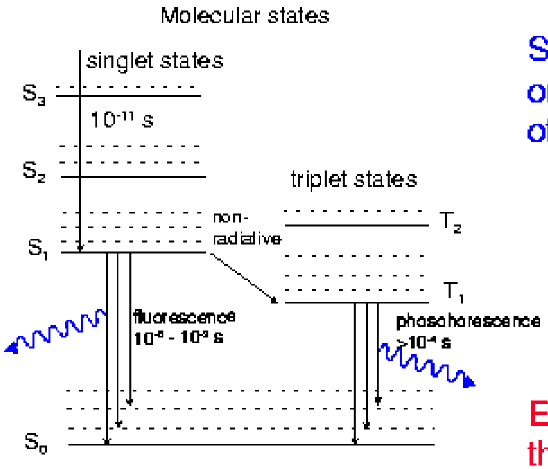
(From Harshaw catalog)

1b. Liquid noble gases (LAr, LXe, LKr)

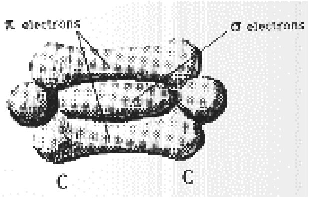


also here one finds 2 time constants: few ns and 100-1000 ns, but same wavelength.

Organic Scintillators



Scintillation is based on the 2 π electrons of the C-C bonds.



Emitted light is in the UV range.

Monocrystals: naphtalene, anthracene, p-terphenyl….

Liquid and plastic scintillators

They consist normally of a solvent + secondary (and tertiary) fluors as wavelength shifters.

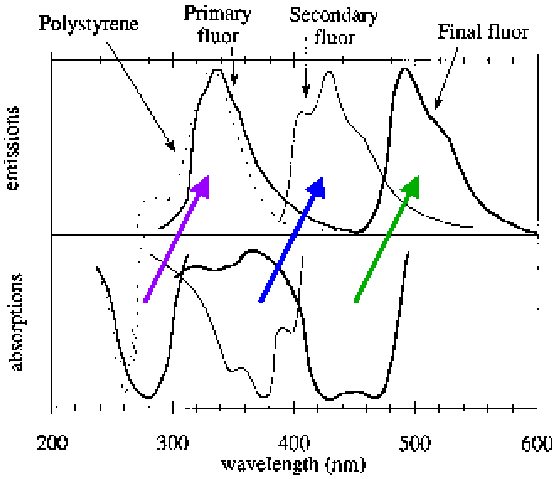
Fast energy transfer via non-radiative dipole-dipole interactions (Förster transfer).

→ shift emission to longer wavelengths

→ longer absorption length and efficient read-out device

Plastic Scintillators

Schematic representation of wave length shifting principle



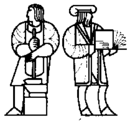
(C. Zorn, Instrumentation In High Energy Physics, World Scientific, 1992)

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	p-terphenyl DPO PBD	POPOP TBP BBO DPS

After mixing the components together plastic scintillators are produced by a complex polymerization method.

Some inorganic scintillators are dissolved in PMMA and polymerized (plexiglas).



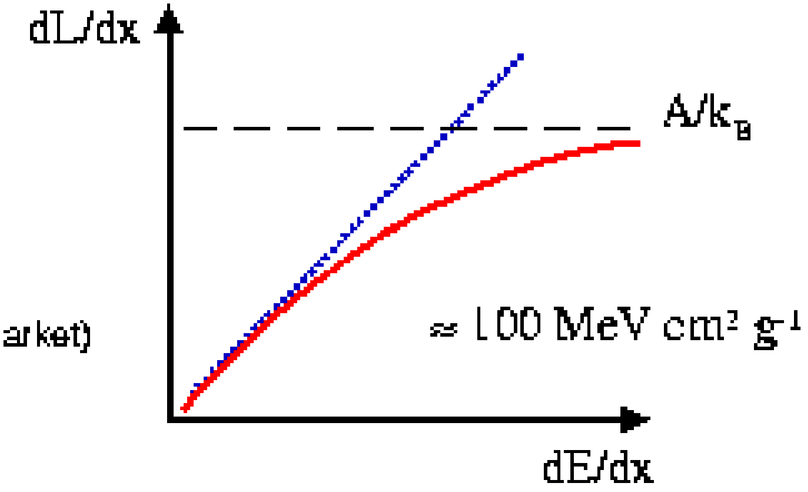
Non-linear Effects in Plastic Scintillators

The response of plastic scintillators is not linear

$$\frac{dL}{dx} = \frac{A \cdot dE/dx}{1 + k_B \cdot dE/dx}$$ Birk's formula

(J.B. Birks, Proc. Phys. Soc. A64, 874 (1951))

(Also other models and parameterizations on the market)



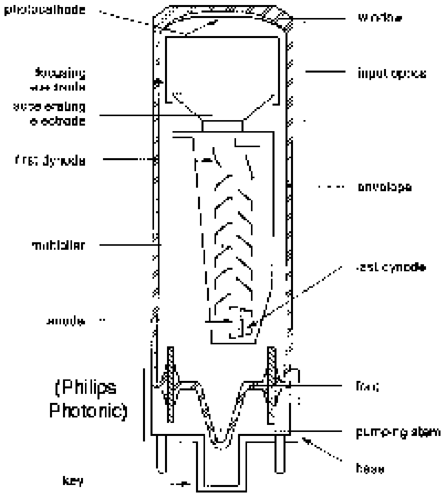
The light yield is reduced by recombination and quenching effects of the excited molecules.

Effect ∝ density of excited molecules ∝ *dE/dx*

Photodetectors

- Photomultiplier Tubes (PMT)
  - fast response time
  - large areas
  - bulky and unstable
- Photodiode
  - high quantum efficiency
  - large areas difficult
- Avalanche Photodiode
  - high quantum efficiency
  - high gain
  - large areas difficult

basic principle:



(Philips Photonic)

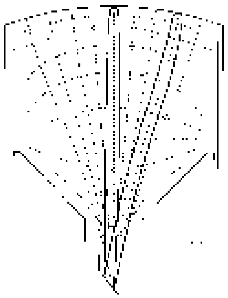
main phenomena:

- photo emission from photo cathode.
  $Q.E. = N_{p.e.}/N_{photons}$
- secondary emission from dynodes.
  dynode gain g=3-50 (f(E))
  total gain $M = \prod_{i=1}^{N} g_i$

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

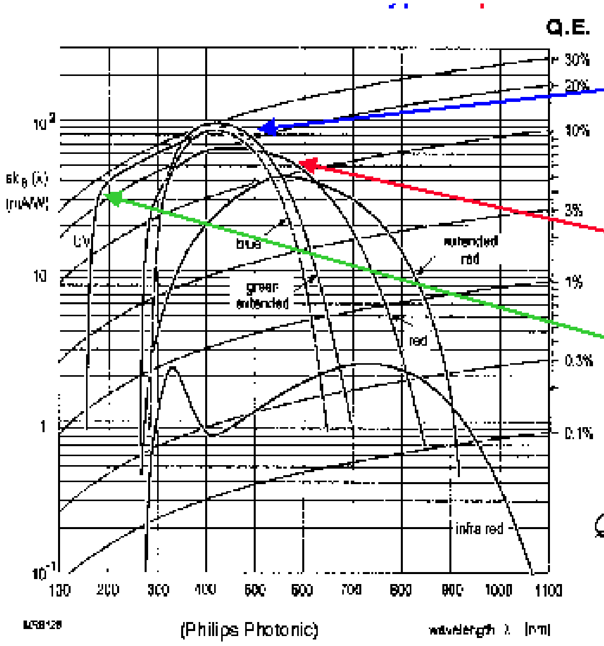
"Fast" PM's require well designed input optics to limit chromatic and geometric aberrations
→ transit time spread < 200 ps

PM's are in general very sensitive to B-fields, even to earth field (30-60 µT). µ-metal shielding required.



Equi-potentials and trajectories in a fast input system

Quantum Efficiencies of Cathodes



(Philips Photonic)

Bialkali

SbK$_2$Cs

SbRbCs

Multialkali

SbNa$_2$KCs

Solar blind

CsTe

(cut by quartz window)

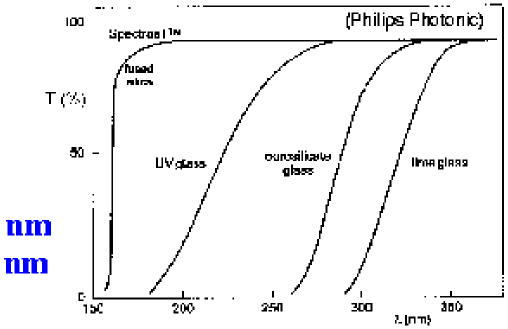
$$Q.E.(\%) \approx 124 \cdot \frac{sk_e(mA/W)}{\lambda(nm)}$$

Transmission of various PM windows

not shown:

MgF$_2$: cut @115 nm

LiF: cut @105 nm



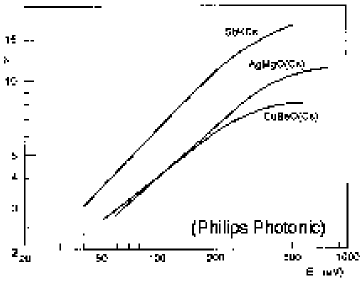
Energy Resolution of PMT

The energy resolution is determined mainly by the fluctuation of the number of secondary electrons emitted from the dynodes.

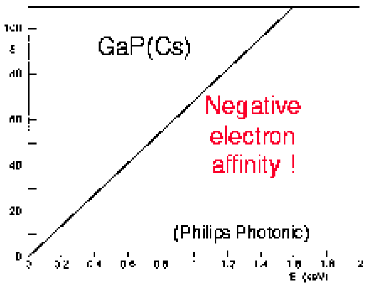
Poisson distribution: $P(\bar{n}, m) = \frac{\bar{n}^{m} e^{-m}}{m!}$

Relative fluctuation: $\frac{\sigma_{n}}{\bar{n}} = \frac{\sqrt{\bar{n}}}{\bar{n}} = \frac{1}{\sqrt{\bar{n}}}$

Fluctuations biggest, when $\bar{n}$ small ! → First dynode !

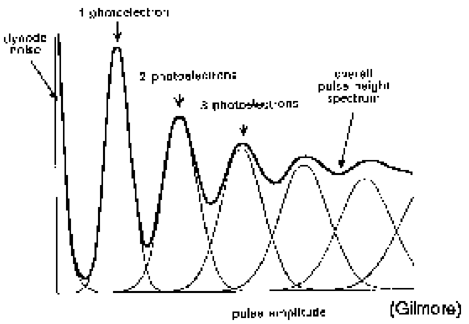


(Philips Photonic)



Negative electron affinity !

(Philips Photonic)

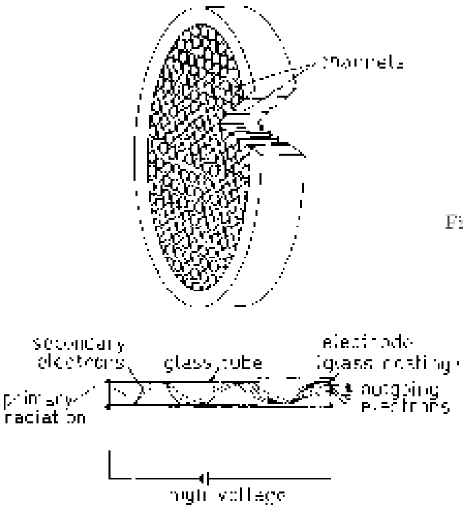


(Gilmore)

Illustration of a pulse height spectrum of a PM. First dynode: δ = 25

MCP

Micro Channel plates



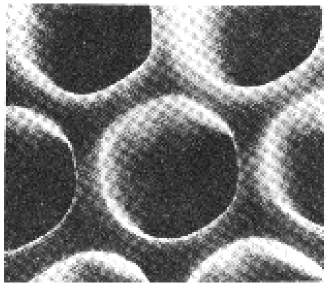
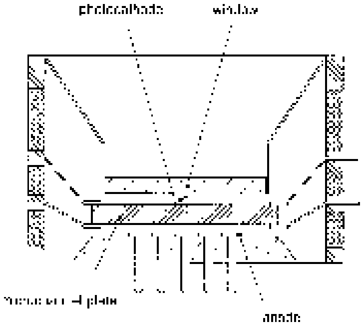


Fig. 5.6. Microphotograph of microchannels [384].



(Philips Photonics)

- \+ fast signal (transit time spread ≈ 50 ps),
- \+ less sensitive to B-field (0.1 T)
- \+ 2-dimensional readout possible
- \- limited life time (0.5 C/cm^2)
- \- limited rate capability (µA/cm^2)

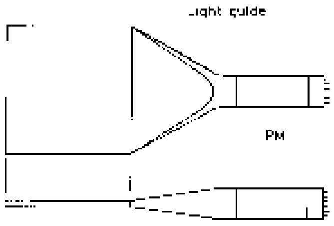
Readout of Scintillators

Readout has to be adapted to geometry and emission spectrum of scintillator.

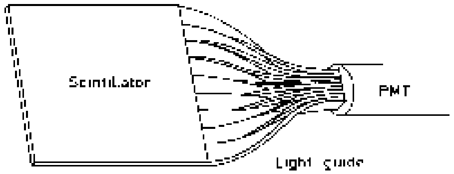
Geometrical adaptation:

- Light guides: transfer by total internal reflection

  (+outer reflector)

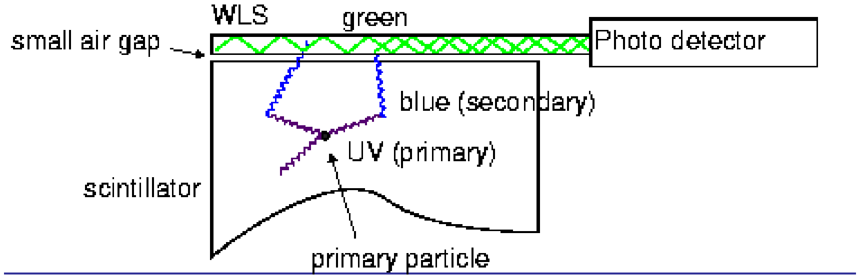


“fish tail”



adiabatic

- wavelength shifter (WLS) bars



Fiber Readout

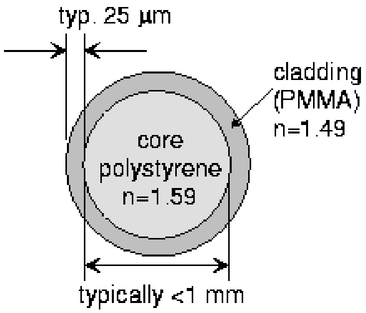
Widely used wavelength shifters:

BBQ, Y7, K27, embedded in PMMA

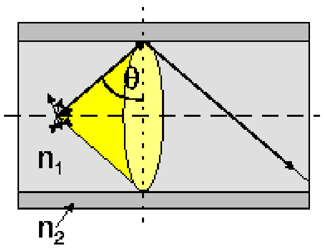
- absorption around 400 nm
- emission around 500 nm
- big Stokes shift → minimal overlap between absorption and emission spectrum → long absorption length for emitted spectrum.

Conversion efficiencies around 10-20%.

◆ Fibers



light transport by total internal reflection



$\theta \geq \arcsin\frac{n_2}{n_1} \approx 69.6^\circ$ $\frac{d\Omega}{4\pi} = 3.1\%$ in one direction

minimize n_{cladding}.

Ideal: air (n=1), but impossible due to surface imperfections

X-ray transmission measurements

- good geometry experiments
- detector efficiency
- dynamic range
- stability
- counting vs. integration
- statistical noise
- other noise sources

X-ray detectors for tomography

- scintillators
  - cadmium tungstate
  - sodium iodide
  - cesium iodide
- xenon detectors
  - ionization
  - scintillation

Positron Emission Tomography

- efficiency at 511 keV
- time resolution important
- design tradeoffs

Design decisions

- statistical noise
- dynamic range
- energy resolution
- artifacts
- stability
- requirements for electronics