Light-based Radiation Detection, Detection of Light

Alfredo D. Ferella

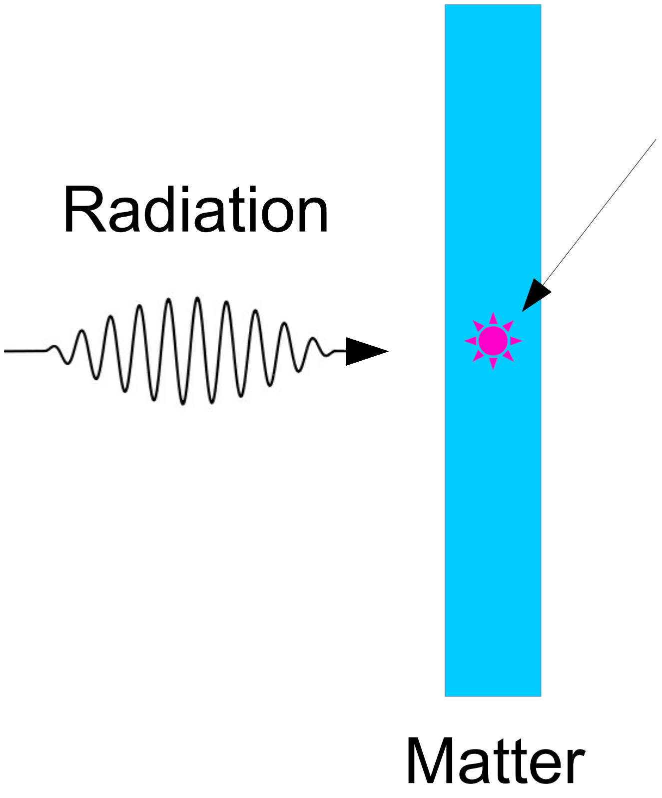
PID – LNGS

2019/10/22

Outline

- Scintillators: various types
- Photomultipliers

Signal generation following energy deposition



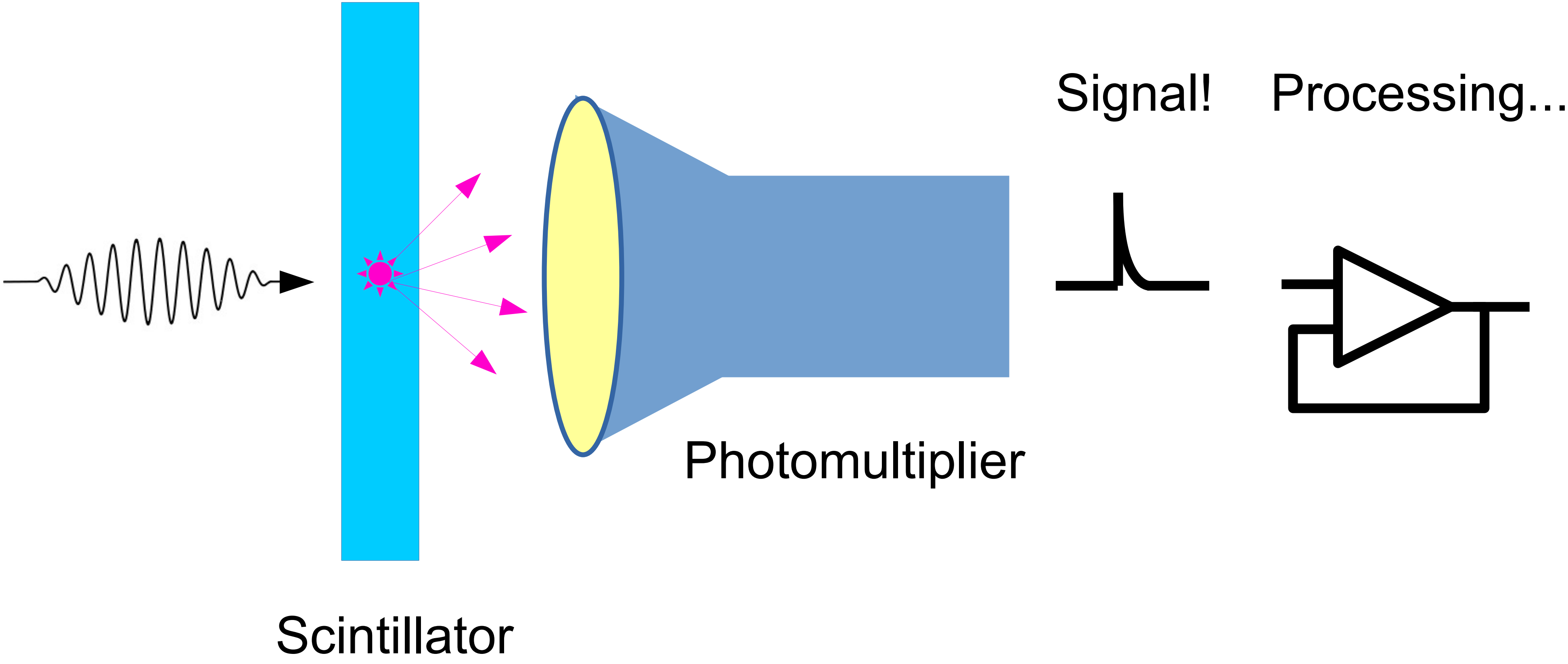
Radiation-matter Interaction: Particle deposits energy in detector’s sensitive volume

… now what?

Manual readout of scintillation

A *scintillator* is one of the oldest particle detectors for nuclear radiation. In the early times charged particles had been detected by light flashes emitted when the particles impinged on a zinc-sulphate screen. This light was registered with the naked eye. It has been reported that the sensitivity of the human eye can be significantly increased by a cup of strong coffee possibly with a small dose of strychnine.

A less damaging method



Scintillators

Scintillator Characteristics

- Scintillation **efficiency**: conversion of kinetic energy into photons
- **Linearity** of response
- **Transparency** to scintillation photons
- Luminescence **decay time**
- Coupling to photodetector
- Cost, size, other physical characteristics

Table 8.1 Properties of Some Commercially Available Organic Scintillators

Eljen	Bicron	Light Output %Anthracene*	Wavelength of Max Emission (nm)	Decay Constant (ns)	Attenuation Length (cm)	Refractive Index
Crystal						
Anthracene		100	447	30		1.62
Stilbene		50	410	4.5		1.626
Plastic						
EJ-212	BC-400	65	423	2.4	250	1.581
EJ-204	BC-404	68	408	1.8	160	1.58
EJ-200	BC-408	64	425	2.1	380	1.58
EJ-208	BC-412	60	434	3.3	400	1.58
	BC-420	64	391	1.5	110	1.58
EJ-232	BC-422	55	370	1.4	8	1.58
	BC-422Q	11	370	0.7	< 8	1.58
	BC-428	36	480	12.5	150	1.58
	BC-430	45	580	16.8	NA	1.58
EJ-248	BC-434	60	425	2.2	350	1.59
	BC-436	52	425	2.2	NA	1.61

Scintillator Categories

Crystal

Plastic

Liquid

Gas

Noble Elements

He, Ne, Ar, Xe

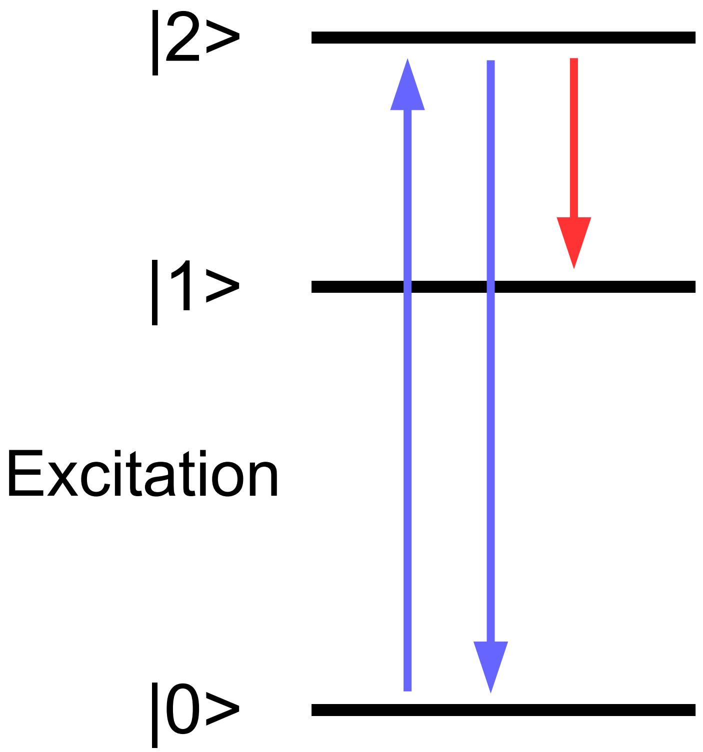
Organics

Anthracene
Stilbene
Other pi-systems

Inorganic

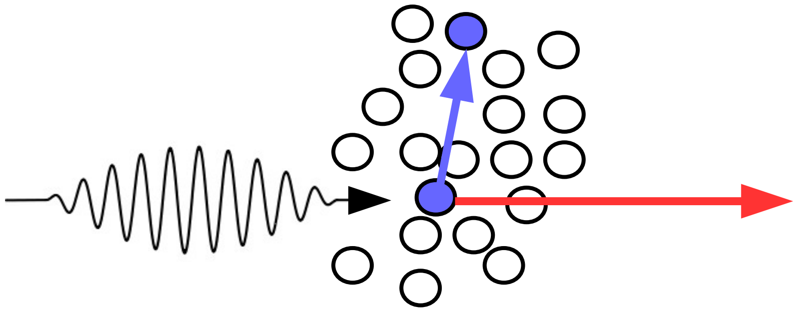
NaI, CsI, BGO...

Fluorescence basics



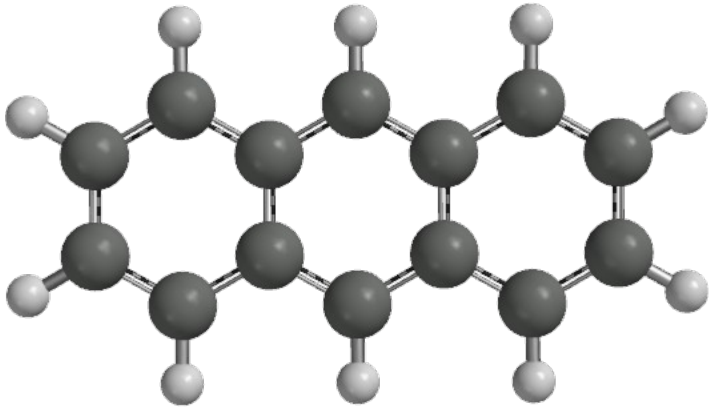
De-excitation:
Fluorescence

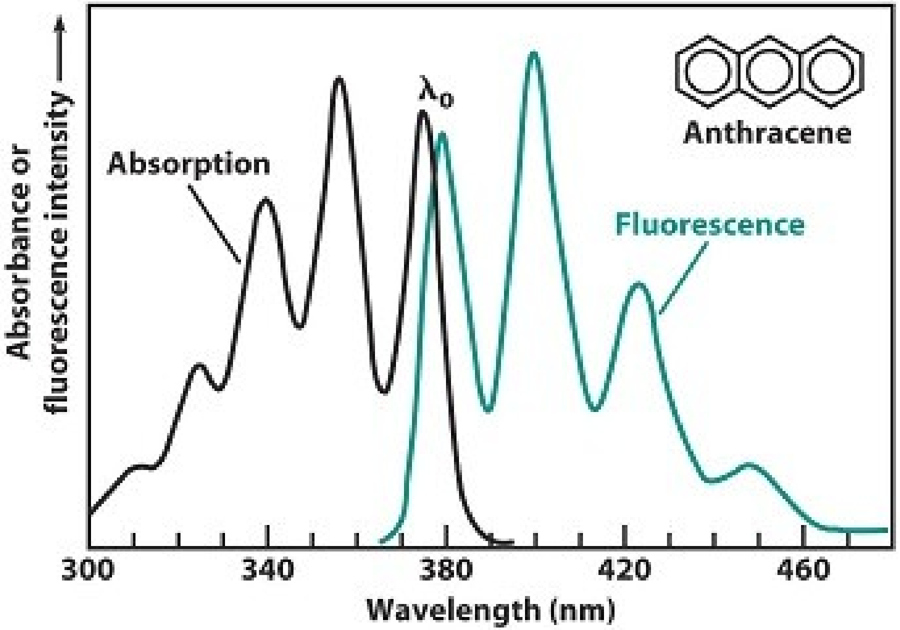
Useful scintillators emit at lower energies than they absorb



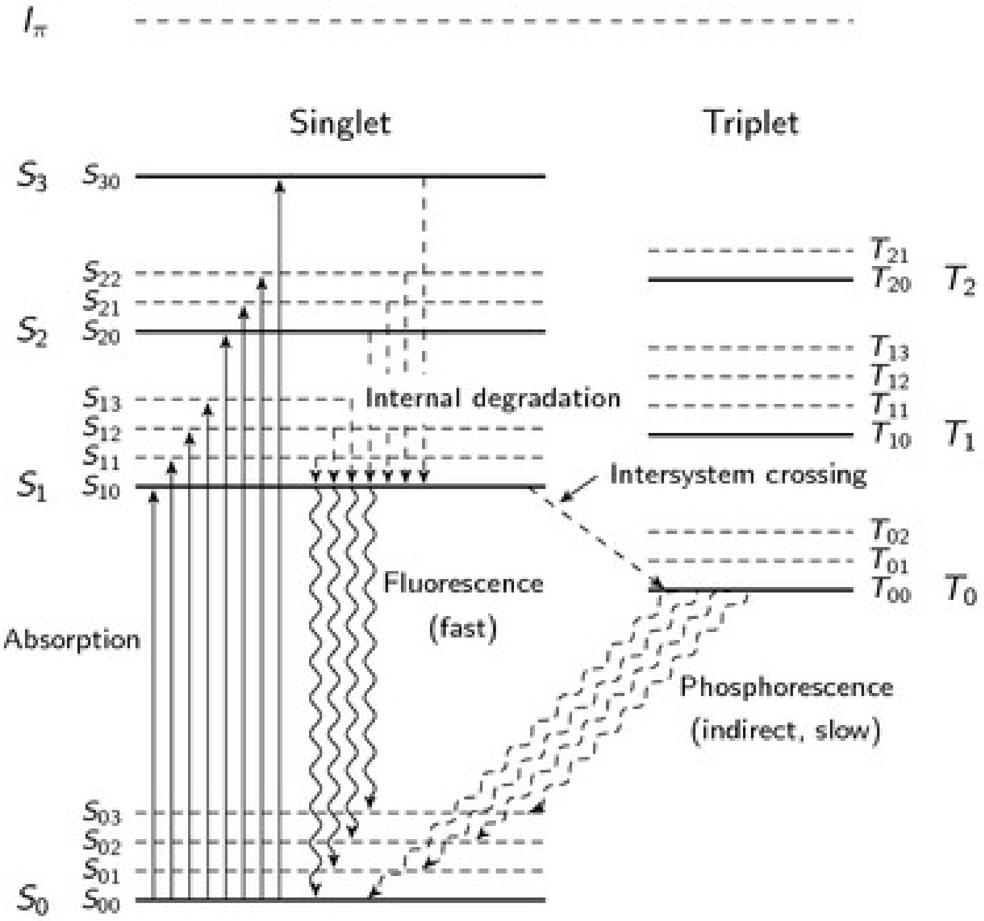
Organic Scintillators

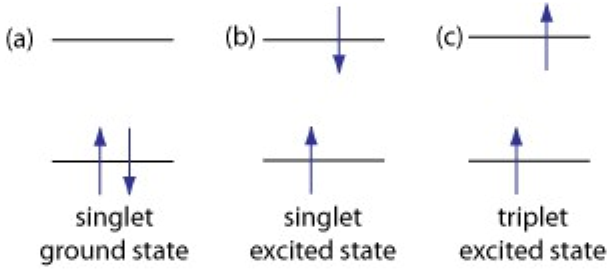
- Anthracene: the prototype
- $C_{14}H_{10}$
- Polycyclic aromatic hydrocarbon

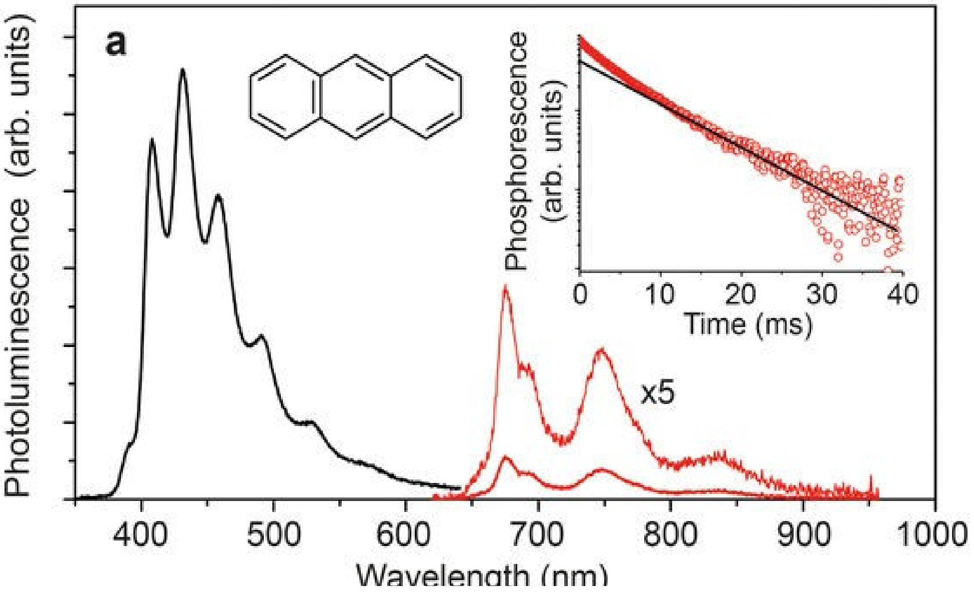




Luminescence from π-bonded molecules





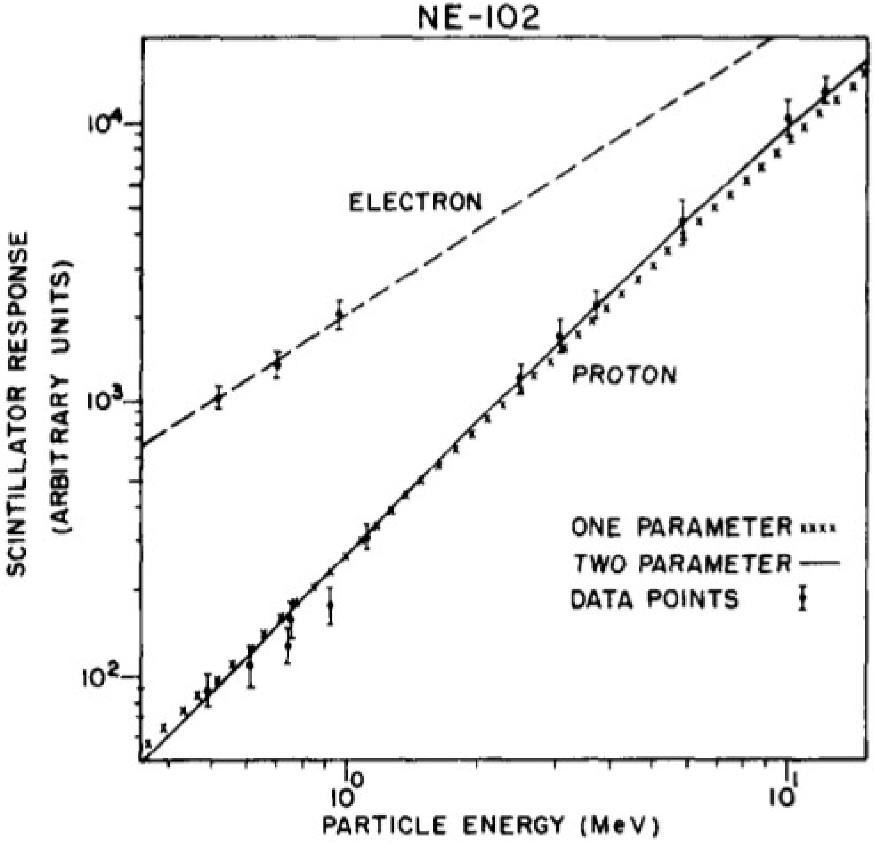


Reineke & Baldo *Sci Rep* **4** 3797 (2014)

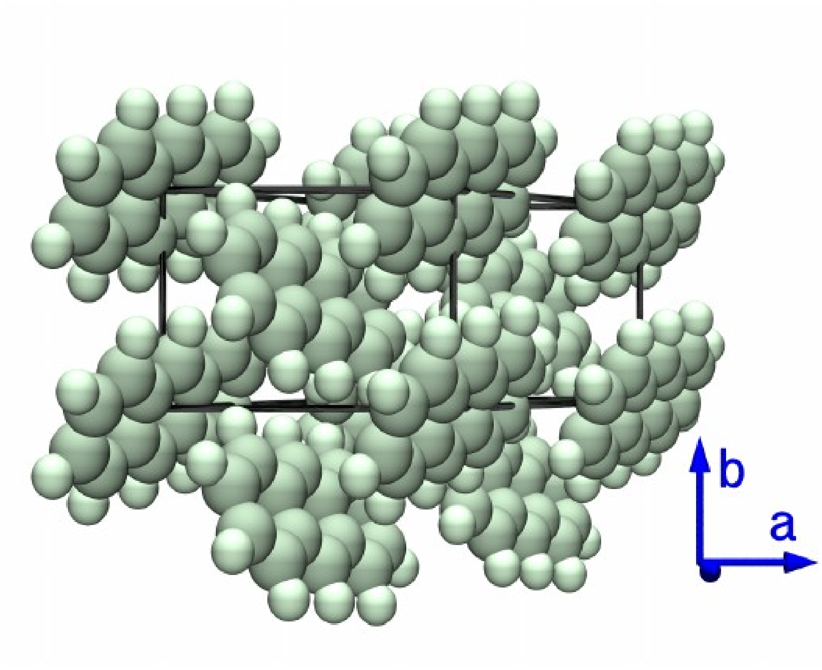
Light output

- Characterized by L_0: photons emitted per MeV deposited energy, typically ~10^4 MeV^{-1} for common materials
- Organic scintillators have non-linear response at high energy density dE/dx due to self-quenching and radiation damage
- Non-linearity characterized by k_B, Birks' formula, k_B~10^3 g/cm^{2}MeV

$$L = L_0 \frac{1}{1 + k_\mathrm{B} \cdot \mathrm{d}E/\mathrm{d}x}$$

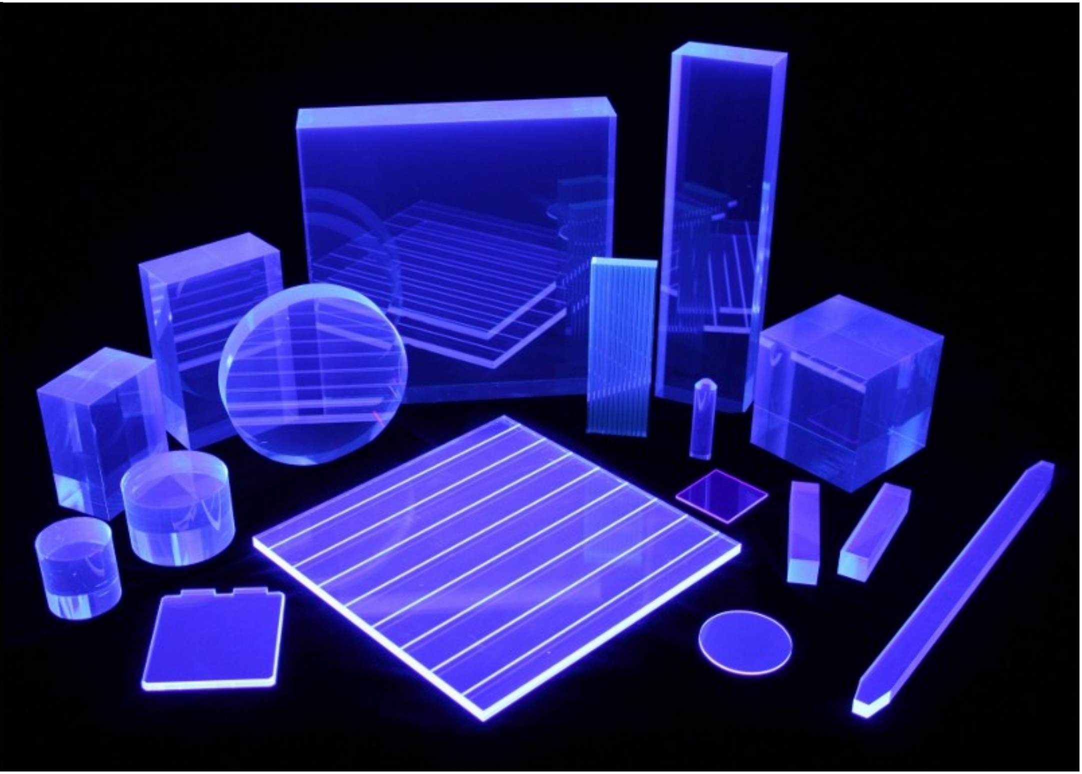


Organic crystal scintillators



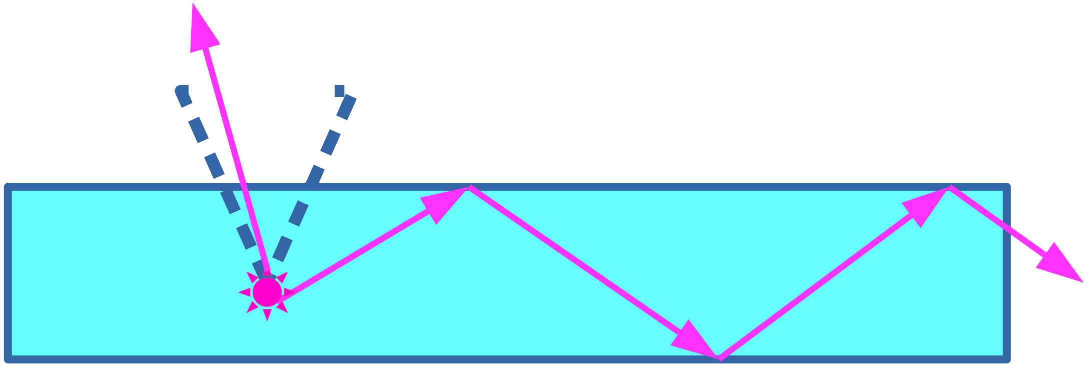
Anthracene crystals

Liquid and plastic organic scintillators

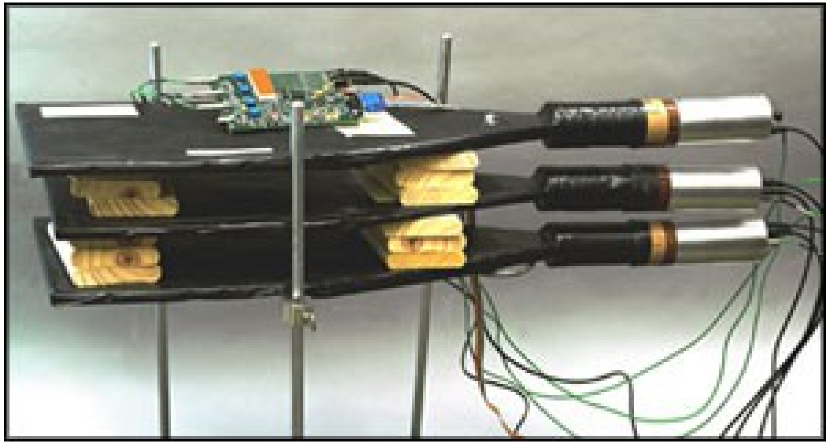


Scale Scale Scale

Typical plastic scintillator setup



Total internal reflection
Critical angle $sin^{-1}(n)$



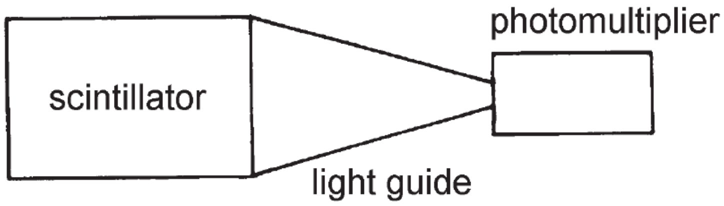
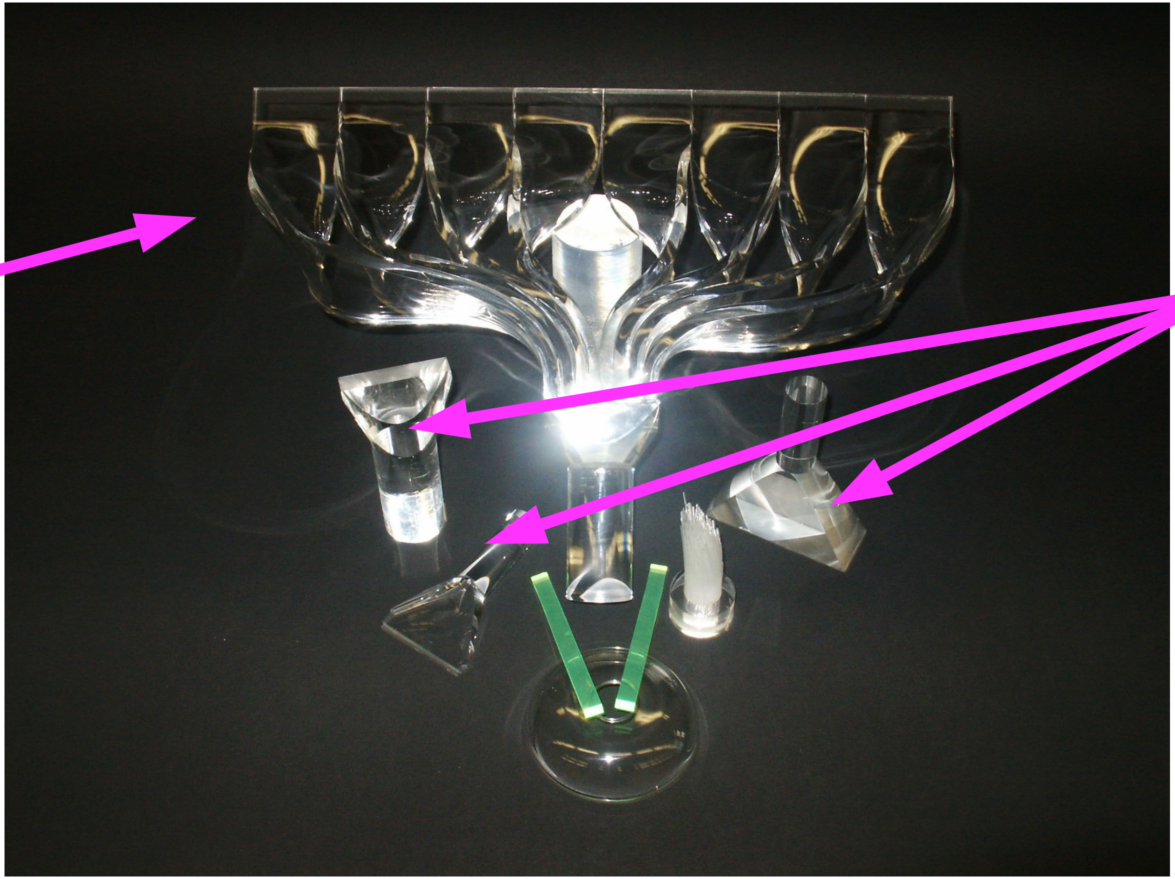


Fig. 5.27. Light readout with a 'fish-tail' light guide.

Light guides

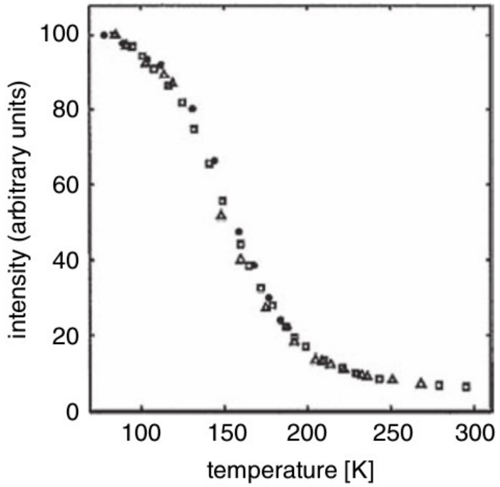
Adiabatic



Fishtail

Inorganic Scintillators

- Single crystal or polycrystaline
- Slower decay times than organics, but brighter
- Some exotic ($$$) crystals are both bright and fast



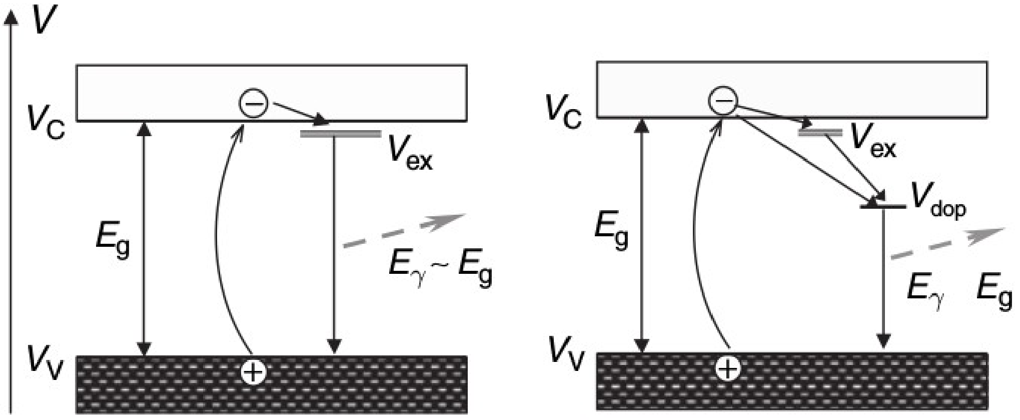
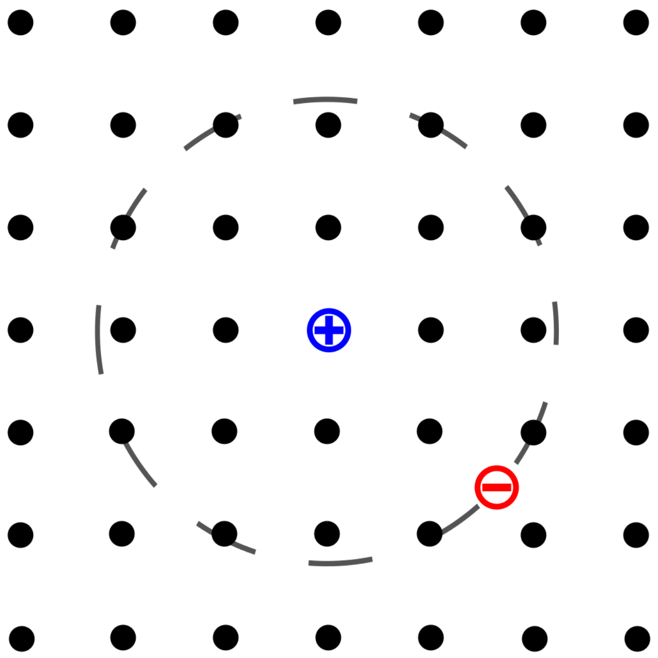


Fig. 5.23. Energy bands in a pure (left) and doped (right) crystal.

Excitons and doping

Exciton



Doping

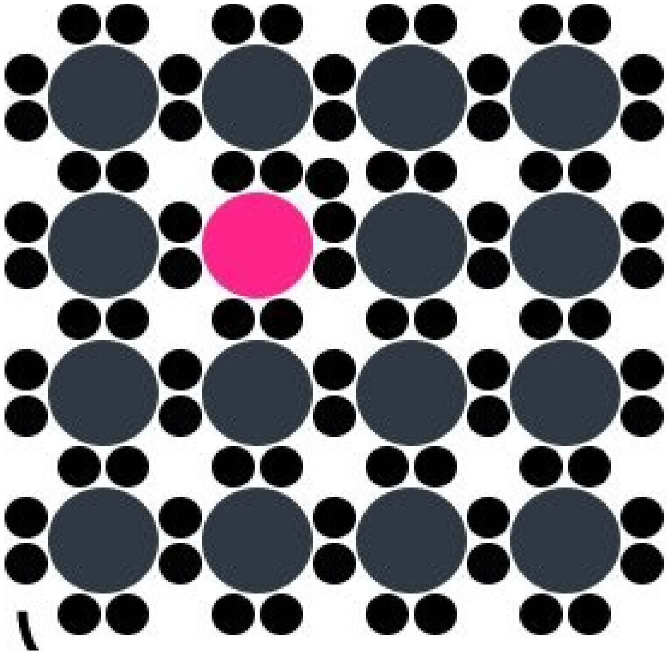
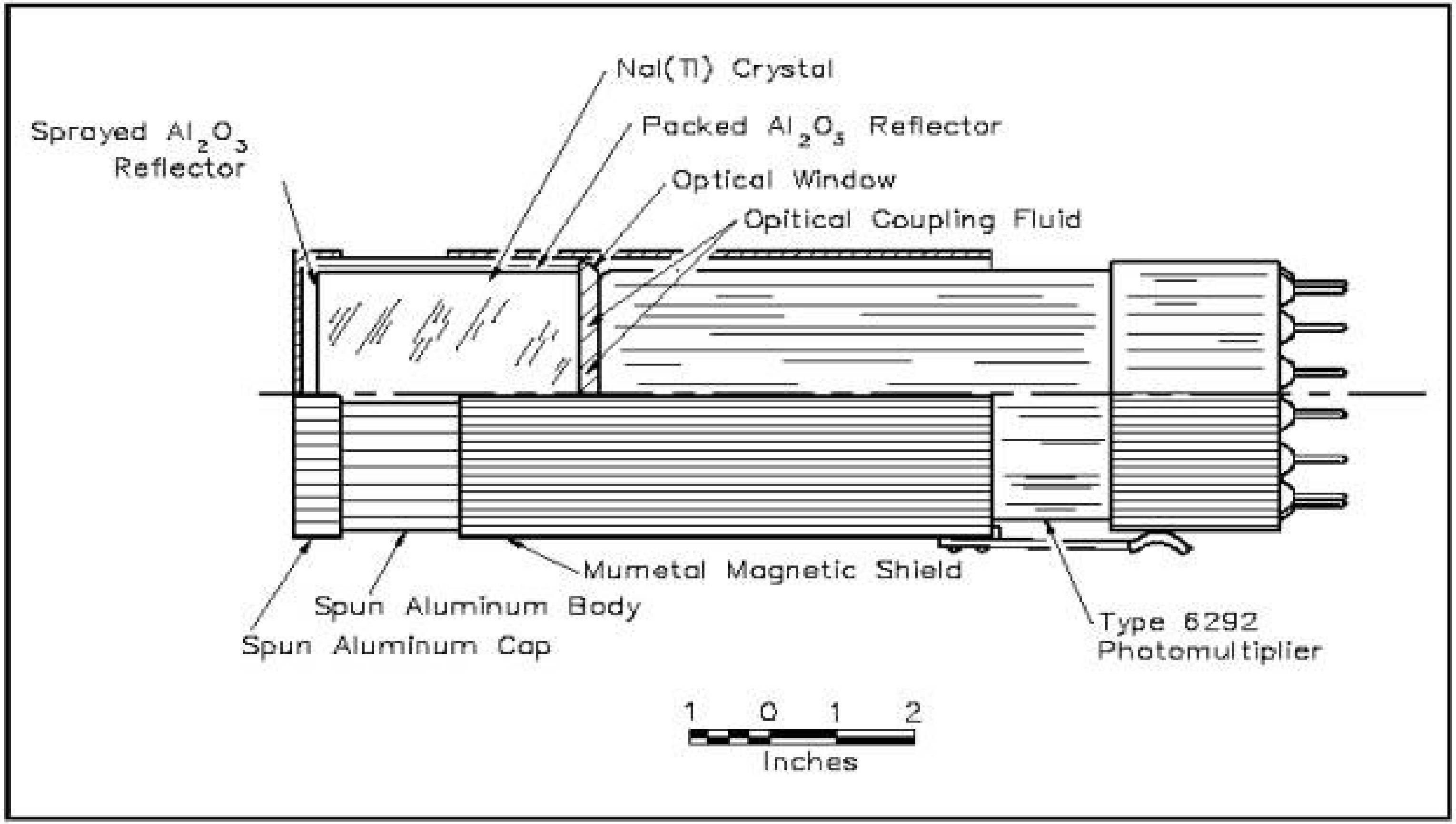


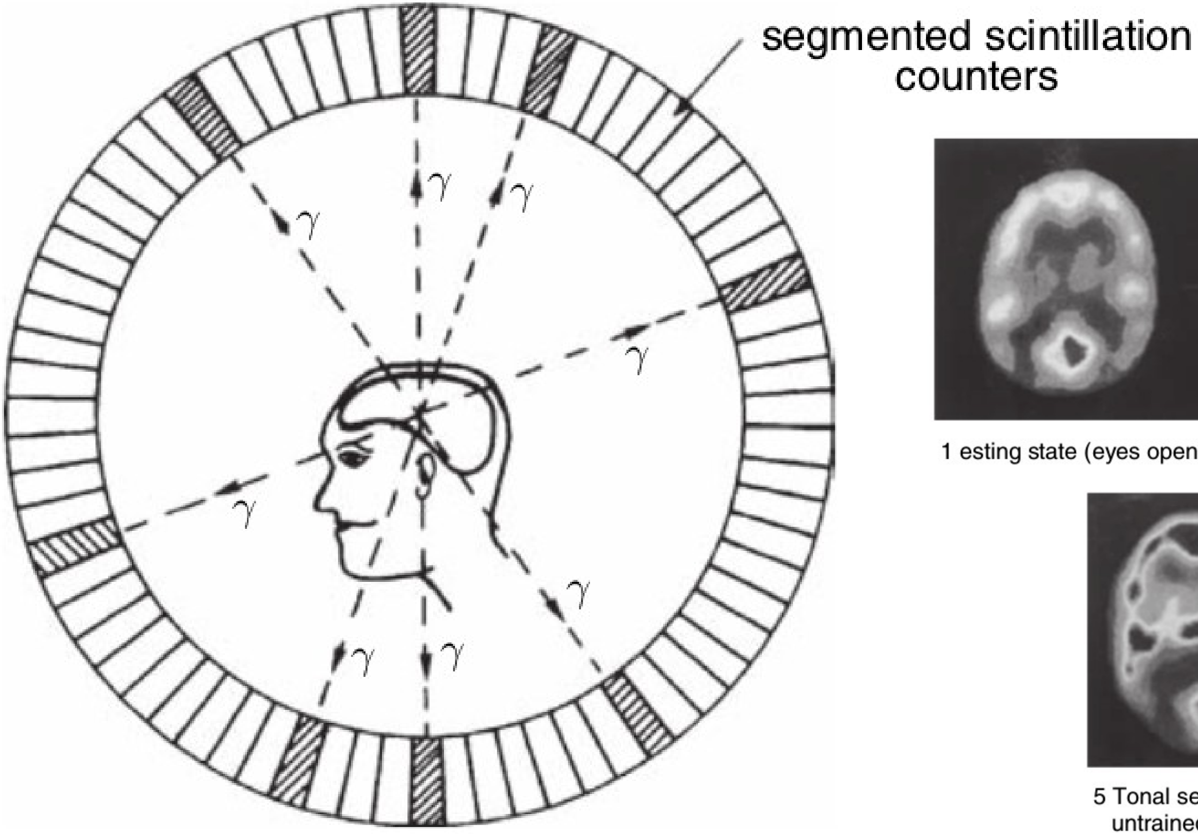
Table 5.2. *Characteristic parameters of some inorganic scintillators [93–98]*

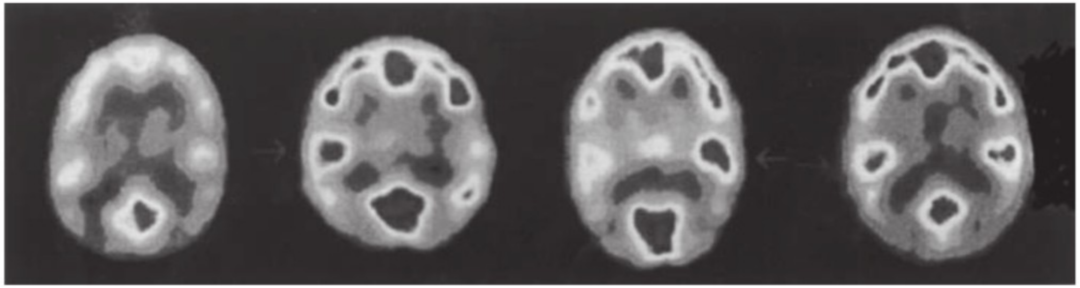
Scintillator	Density ϱ [g/cm^3]	X_0 [cm]	τ_D [ns]	L_{ph}, N_{ph} [per MeV]	λ_{em} [nm]	$n(\lambda_{em})$
NaI(Tl)	3.67	2.59	230	$3.8 \cdot 10^4$	415	1.85
LiI(Eu)	4.08	2.2	1400	$1 \cdot 10^4$	470	1.96
CsI	4.51	1.85	30	$2 \cdot 10^3$	315	1.95
CsI(Tl)	4.51	1.85	1000	$5.5 \cdot 10^4$	550	1.79
CsI(Na)	4.51	1.85	630	$4 \cdot 10^4$	420	1.84
$Bi_4Ge_3O_{12}$ (BGO)	7.13	1.12	300	$8 \cdot 10^3$	480	2.15
BaF_2	4.88	2.1	0.7	$2.5 \cdot 10^3$	220	1.54
			630	$6.5 \cdot 10^3$	310	1.50
$CdWO_4$	7.9	1.06	5000	$1.2 \cdot 10^4$	540	2.35
			20 000		490	
$PbWO_4$ (PWO)	8.28	0.85	10/30	70–200	430	2.20
$Lu_2SiO_5(Ce)$ (LSO)	7.41	1.2	12/40	$2.6 \cdot 10^4$	420	1.82

Crystals are small: direct mounting

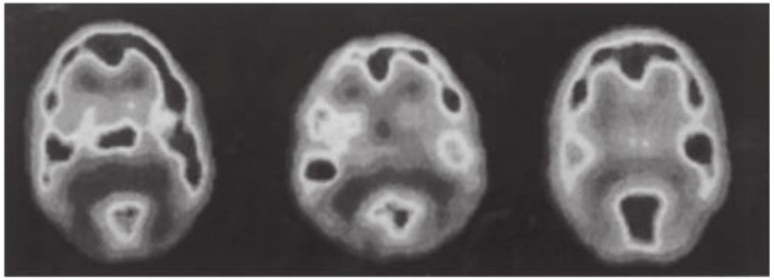


Positron Emission Tomography





1 esting state (eyes open) 2 Language 3 Music 4 Language and music

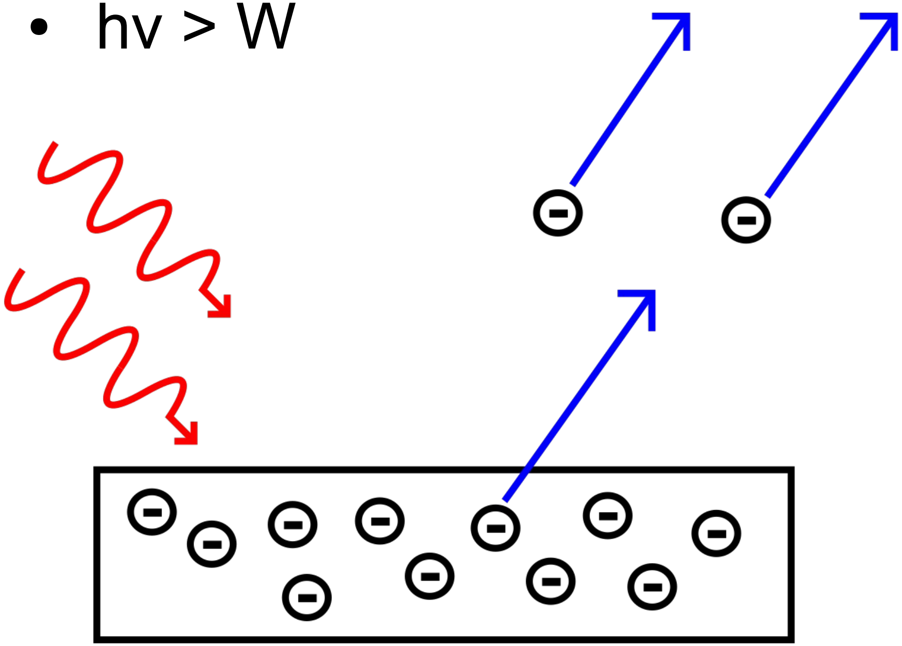


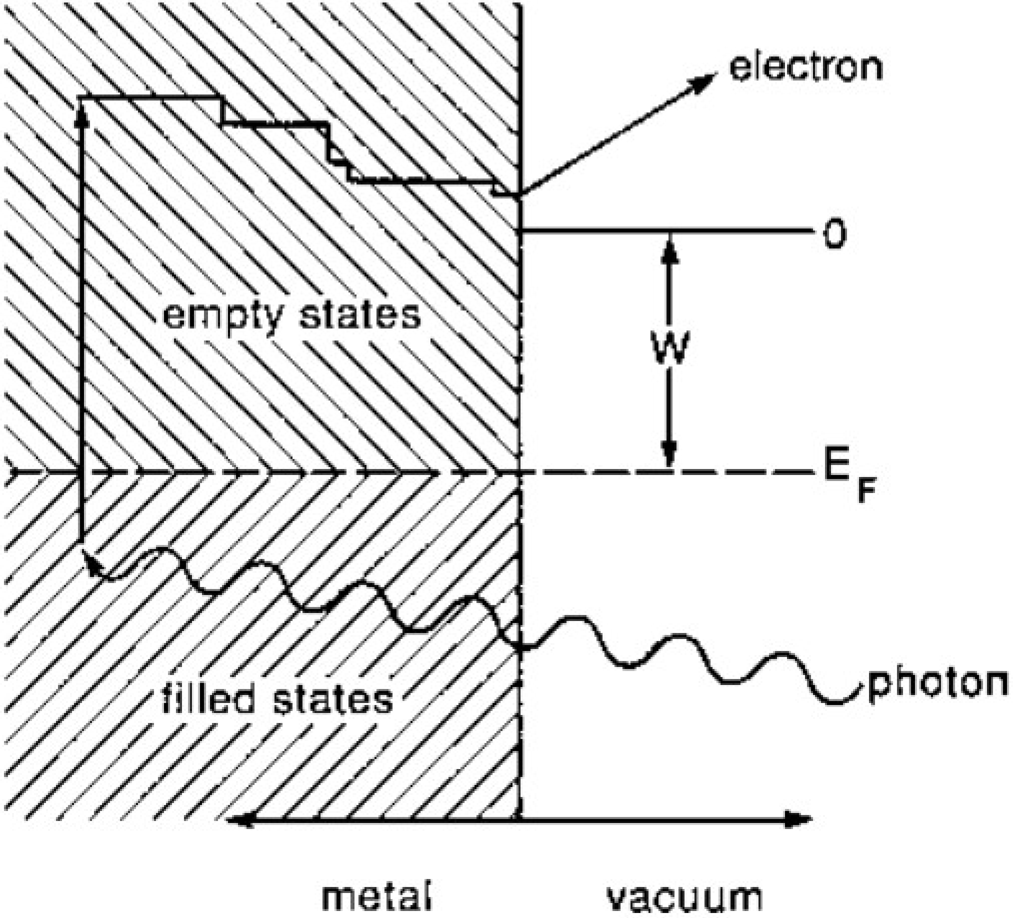
5 Tonal se uence untrained listener 6 Tonal se uence trained listener 7 Tonal uality (chords)

What *is* a photomultiplier tube, and *how* does it work?

The photoelectric effect

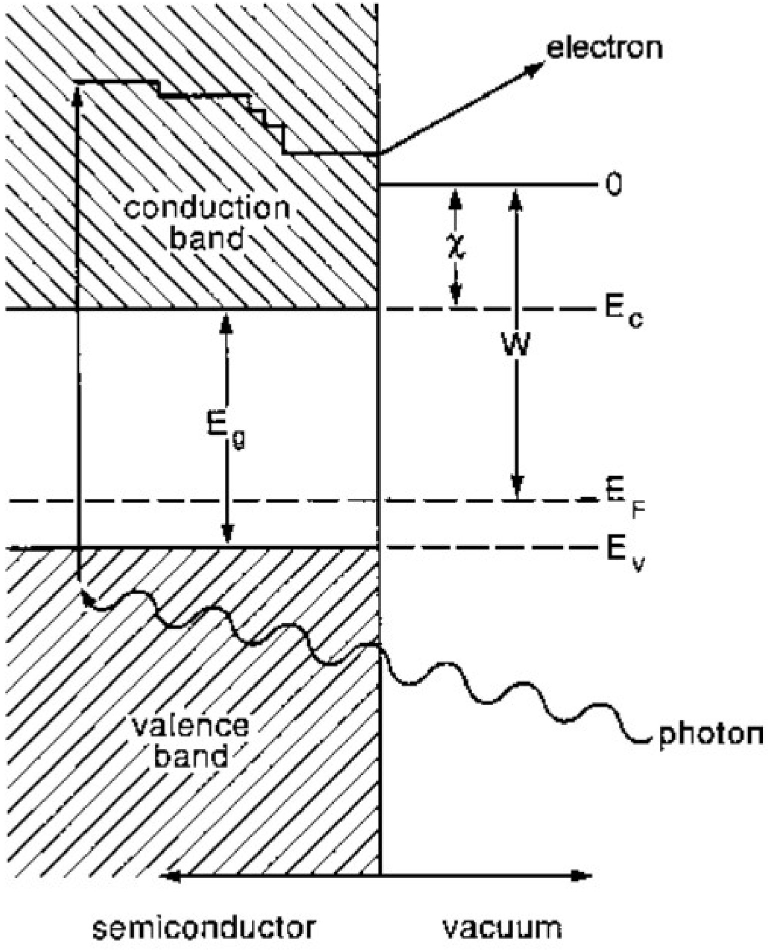
- hv > W



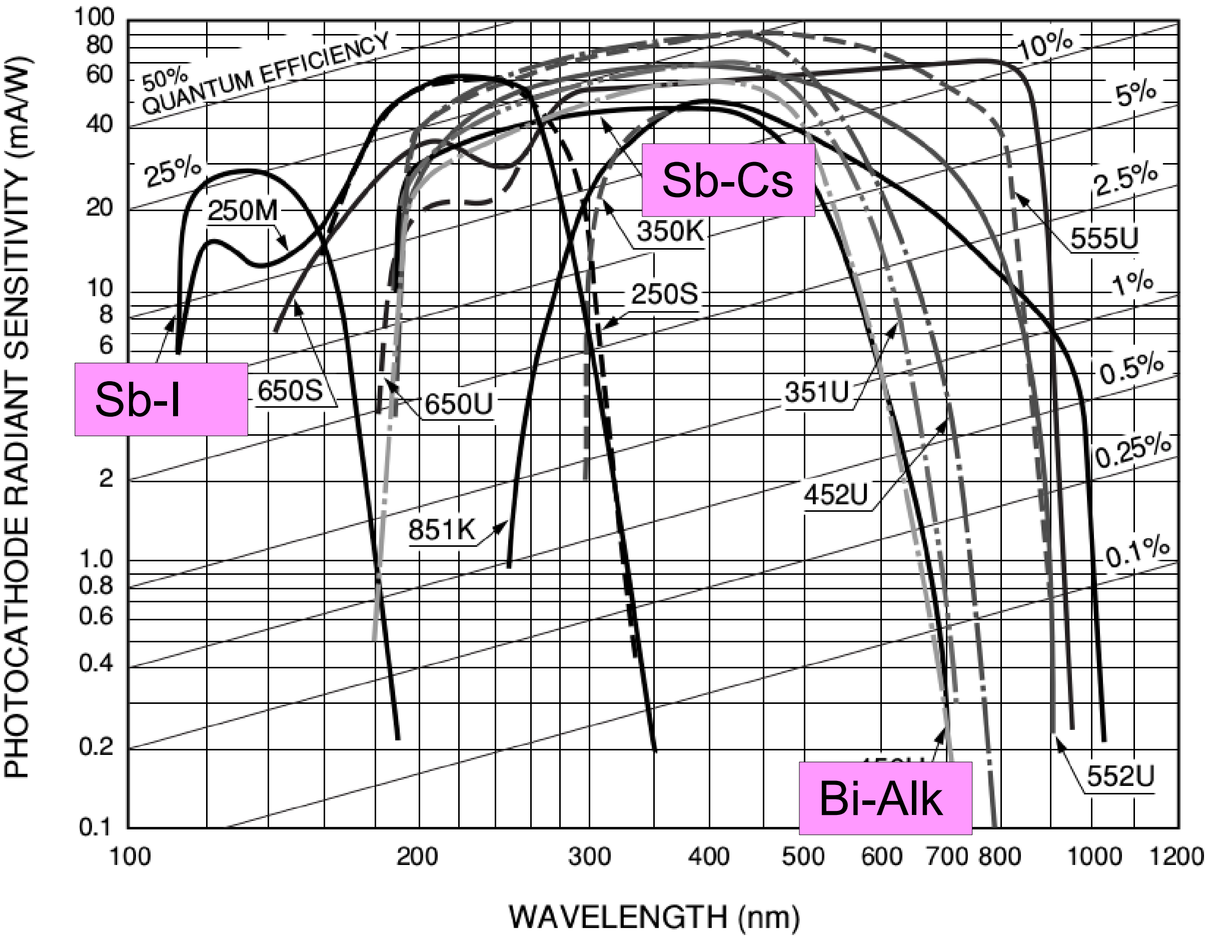


Cathode materials

- Metal is reflective!
- Alkali semiconductors have small W ~2 eV
- Cs-I, Cs-Te UV or "solar blind"
- Sb-Cs or "bialkali" Sb-Rb-Cs/Sb-K-Cs
- Bialkali used most with NaI(Tl) in scintillation counters
- InGaAs and other semiconductor crystals used for IR



Response curves for photocathodes



Quantum efficiency

$$\eta(\nu) = (1-R)\ \frac{P\nu}{k} \cdot \left(\frac{1}{1+1/kL}\right) \cdot Ps$$

where

R : reflection coefficient

k : full absorption coefficient of photons

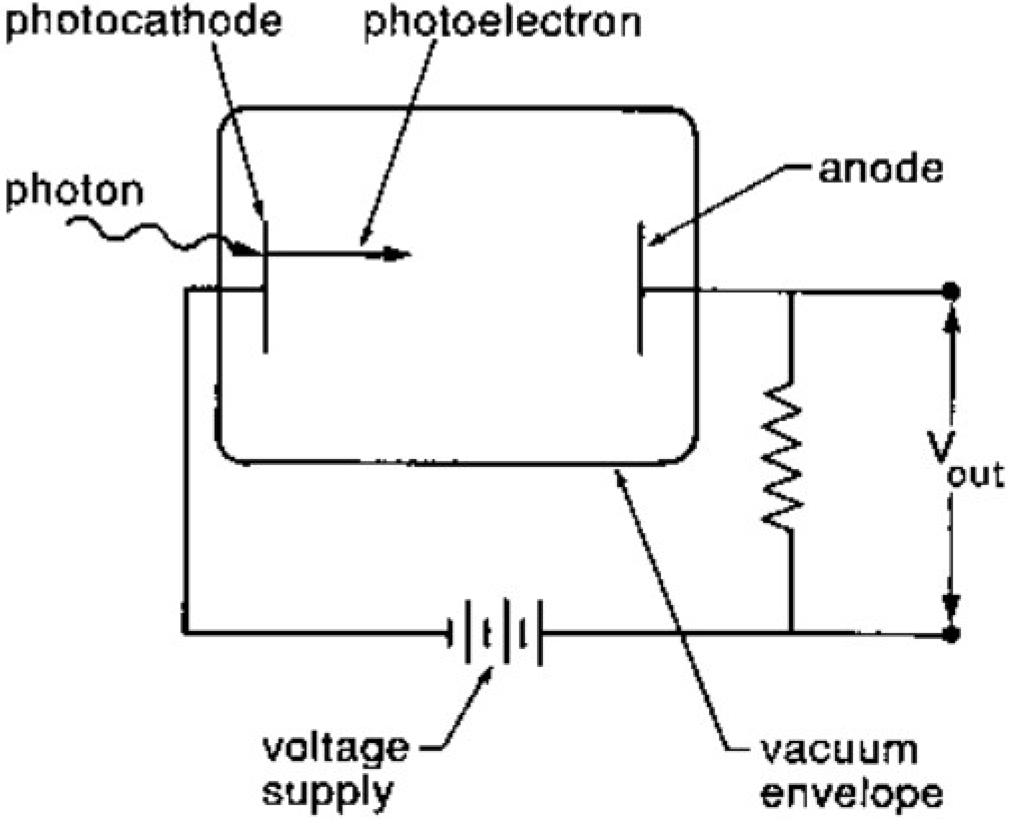
Pν : probability that light absorption may excite electrons to a level greater than the vacuum level

L : mean escape length of excited electrons

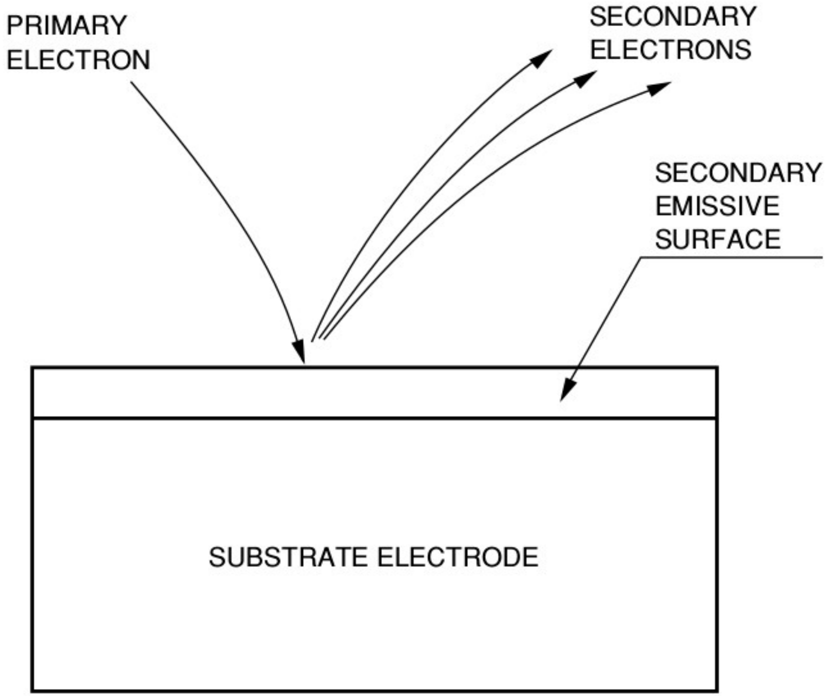
Ps : probability that electrons reaching the photocathode surface may be released into the vacuum

ν : frequency of light

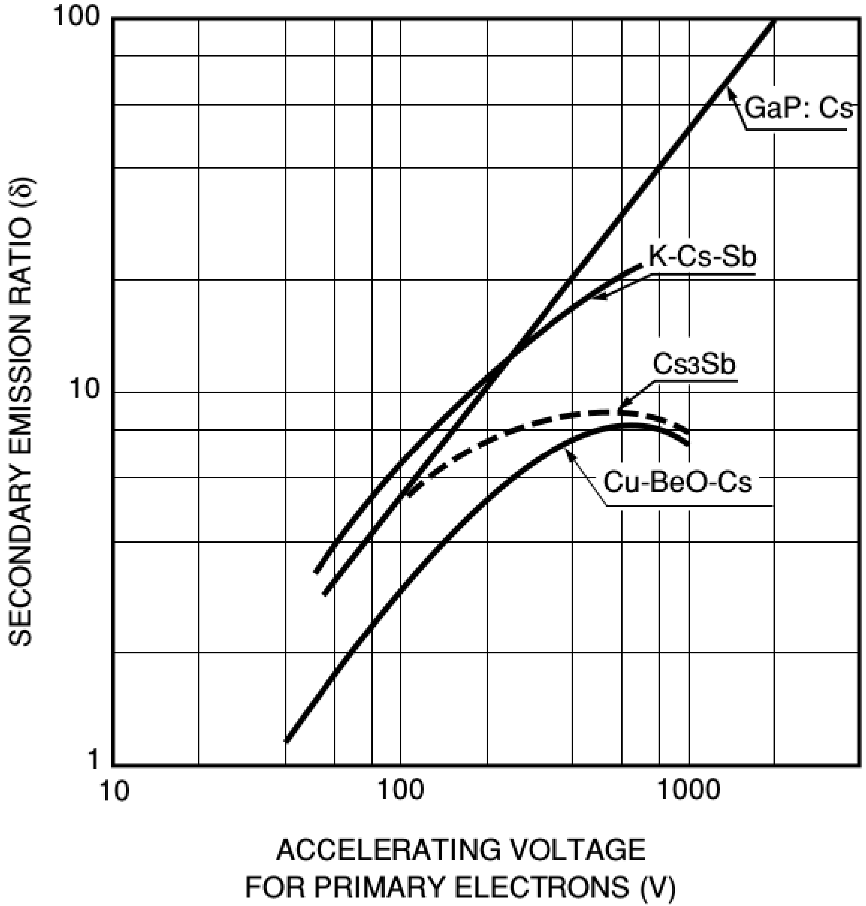
The vacuum photodiode



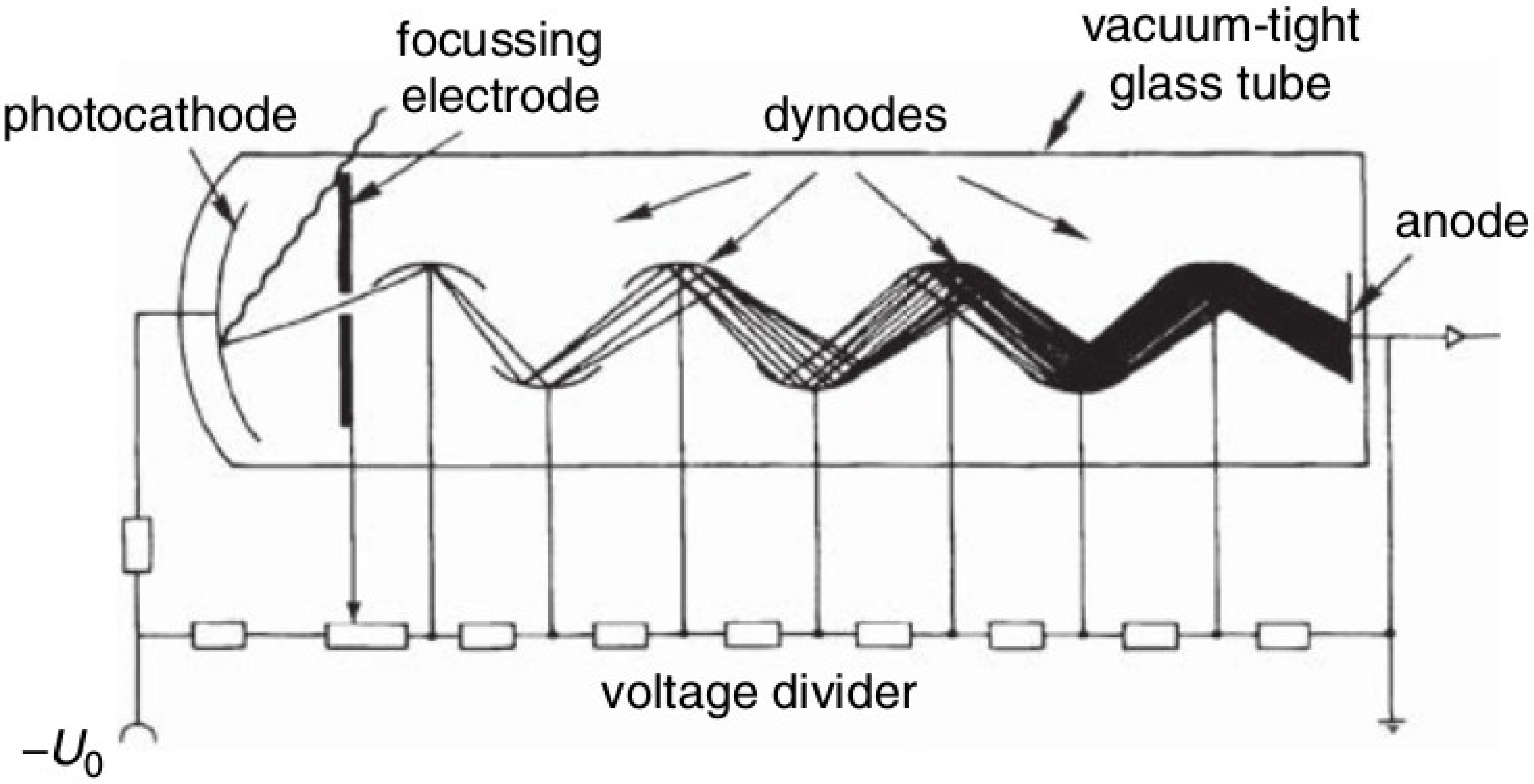
Electron multiplication - gain



Dynode



Finally, the photomultiplier!



Different geometries for different applications

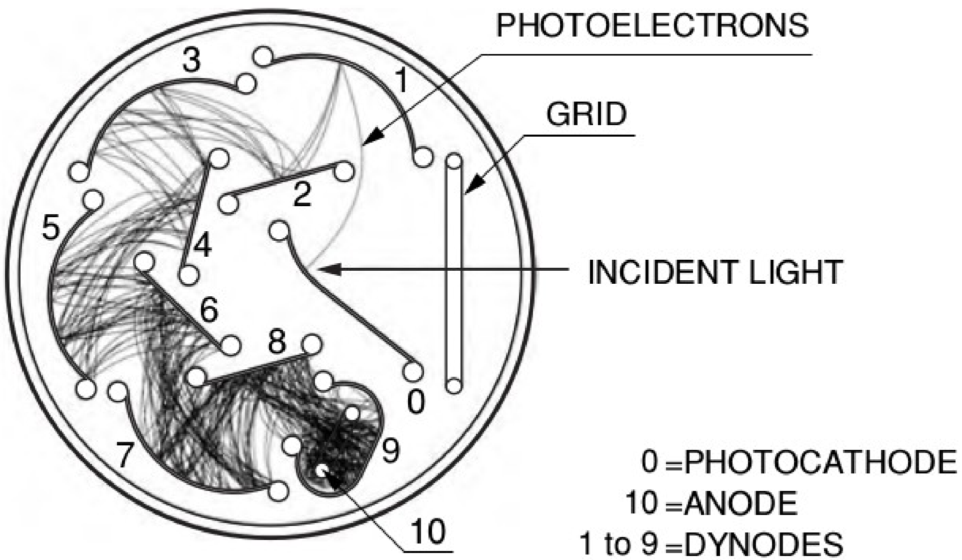


Figure 2-3: Circular-cage type

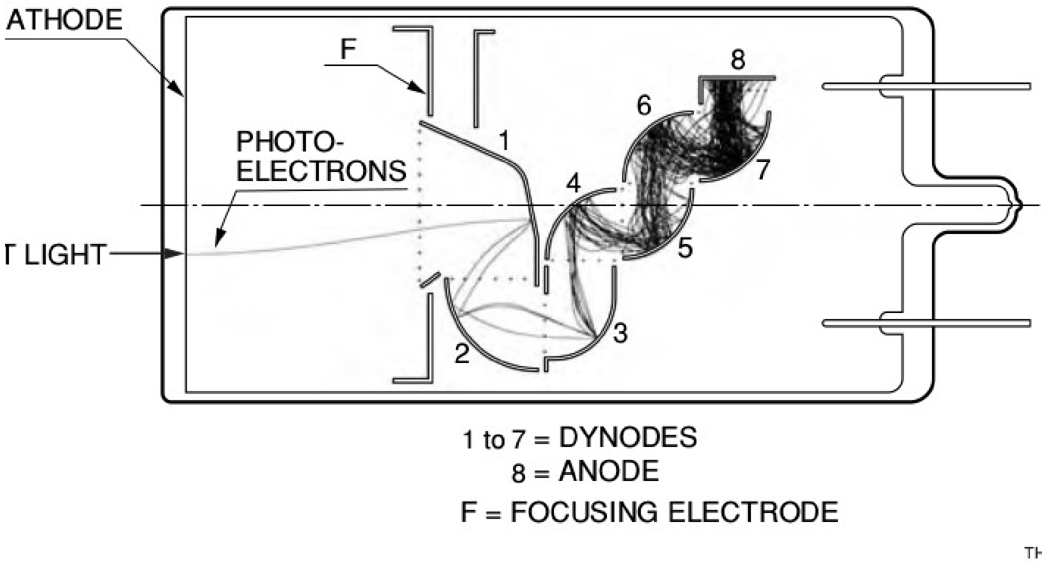


Figure 2-4: Box-and-grid type

Reflection type

Transmission type

Dynode Type	Rise Time (ns)	Pulse Linearity at 2% (mA)	Magnetic Immunity (mT)	Uniform-ity	Collection Efficiency	Features
Circular-cage	0.9 to 3.0	1 to 10	0.1	Poor	Good	Compact, high speed
Box-and-grid	6 to 20			Good	Very good	High collection efficiency
Linear-focused	0.7 to 3	10 to 250		Poor	Good	High speed, high linearity
Venetian blind	6 to 18	10 to 40		Good	Poor	Suited for large diameter
Fine mesh	1.5 to 5.5	300 to 1000	500 to 1500*	Good	Poor	High magnetic immunity, high linearity
MCP	0.1 to 0.3	700	1500*	Good	Poor	high speed
Metal channel	0.65 to 1.5	30	5**	Good	Good	Compact, high speed
Electron bombardment type	Depends on internal semiconductor		—	Very good	Very good	High electron resolution

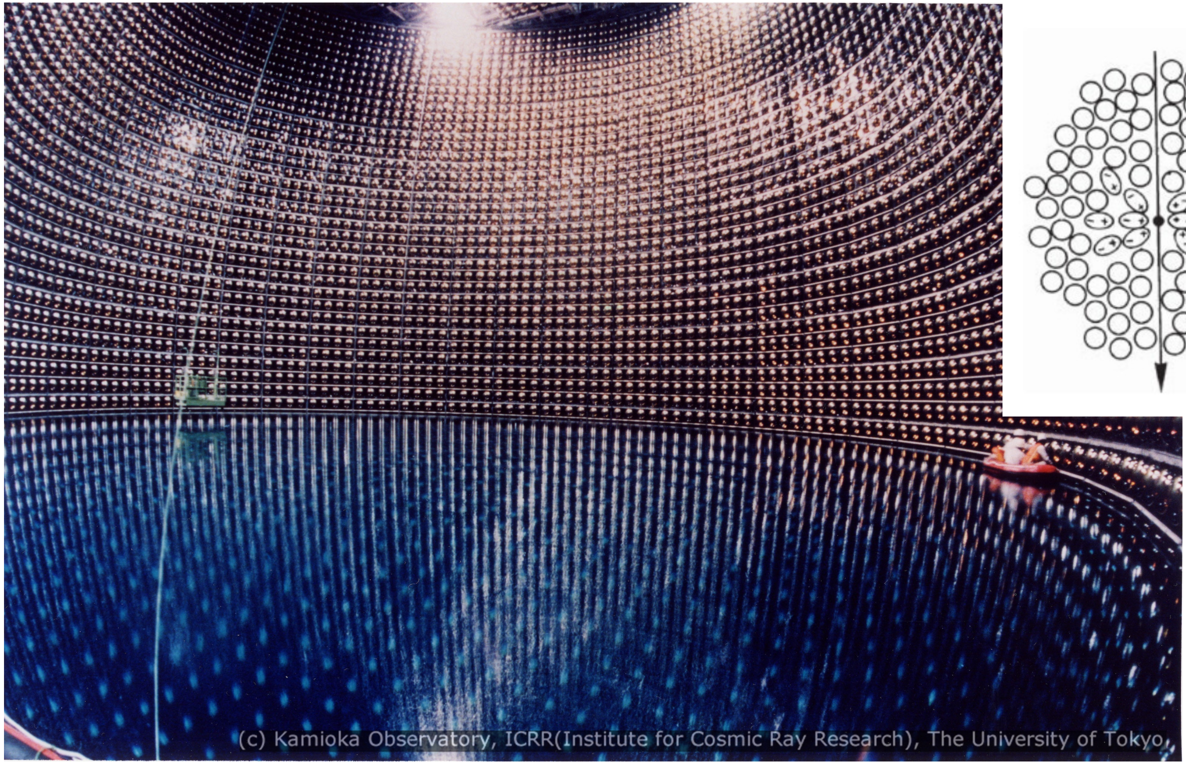
Building a scintillation counter

- What aspects of scintillators and photomultipliers are important to consider when designing / evaluating a detector system?

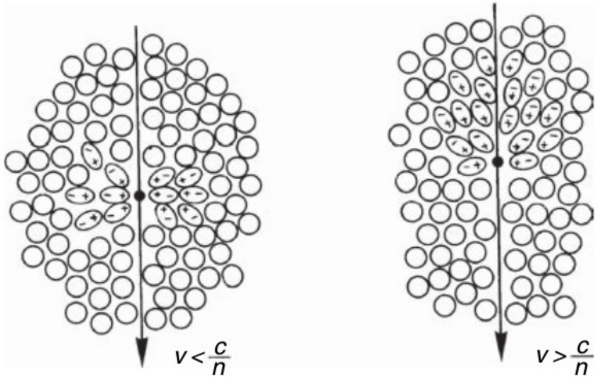
- Scintillator material
- Geometry
- Wavelength shifter?
- Light guide?

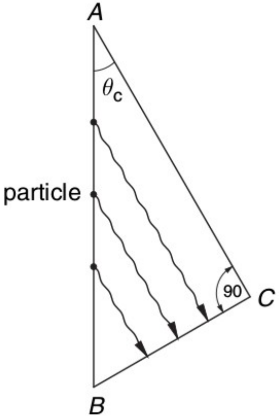
- Window material?
- Photocathode
- Electron optics
- Dynode material, geometry
- Electronics...

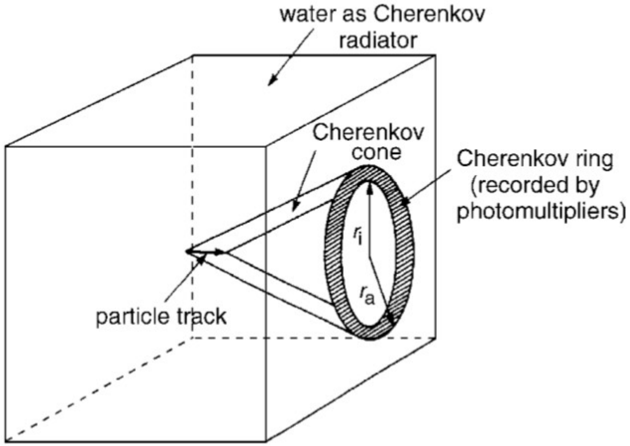
Cherenkov radiation detectors



Super-KamiokaNDE







Cherenkov Neutrino Detectors e.g. IceCube