III. Scintillation Detectors

Sources:

J.B. Birks, *The Theory and Practice of Scintillation Counting*, New York, 1964
G.F. Knoll, *Radiation Detection and Measurement*, New York, 1989
S.E. Derenzo, *Scintillation Counters, Photodetectors and Radiation Spectroscopy*, IEEE Short Course *Radiation Detection and Measurement*, 1997 Nuclear Science Symp.

- Incident particles or photons excite atoms or molecules in the scintillating medium.
- Excited states decay under emission of photons, which are detected and converted into electric signals.

1. Scintillation materials

Both organic and inorganic materials,

can be solid, liquid or gaseous

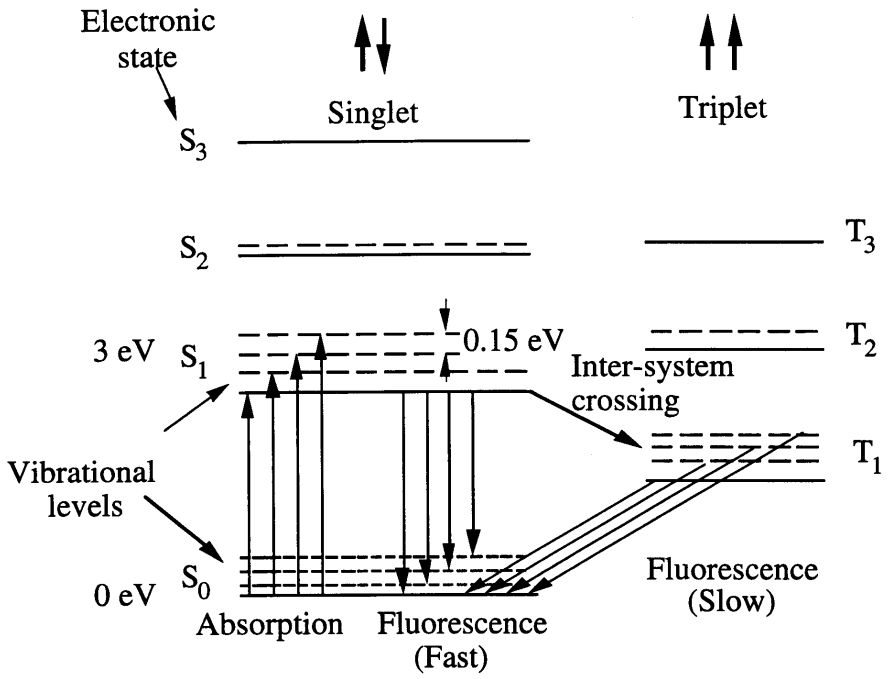
a) organic scintillators (e.g. plastics)

states of interest are energy levels of individual molecules, i.e. no interactions with neighbors

$\Rightarrow$ excitation and emission spectra practically the same whether in solid, liquid or gaseous state.

Typical energy levels

(from Birks, as redrawn by Derenzo)



a) At room temperature practically all electrons in ground state.
(since energy of S1 states >> 0.025 eV)

b) Incident radiation populates S_1 states

vibrational levels within S1 band decay radiation-less to S_1 base state, which in turn decays under emission of light to the S_0 band.

c) S1 can also decay to adjacent triplet levels.
Since their energy is significantly lower, the decay time is much longer.

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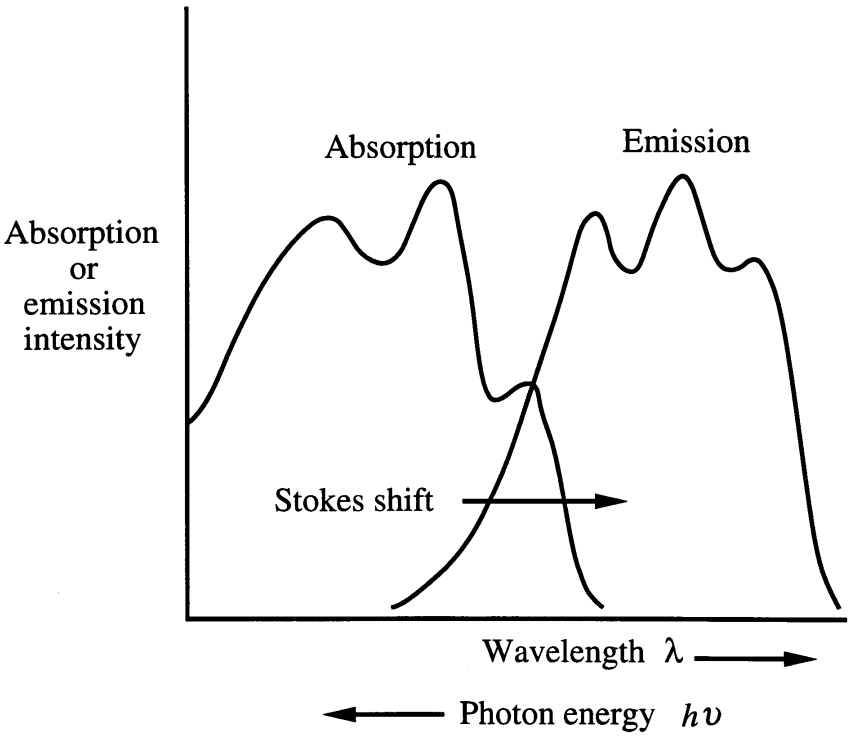
Why isn't emitted light re-absorbed?

Since excitation goes to higher vibrational states in the S_1 band, whereas decay goes from the base S_1 state, the emission spectrum is shifted to lower energies (longer wavelengths).

$\Rightarrow$ only small overlap of emission and absorption spectra



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Time dependence of emitted light

a) non-radiative transfer of energy from vibrational states to fluorescent state

typical time: 0.2 – 0.4 ns

b) decay of fluorescent state

typical time: 1 – 3 ns

$\Rightarrow$ rise with time constant τ_r

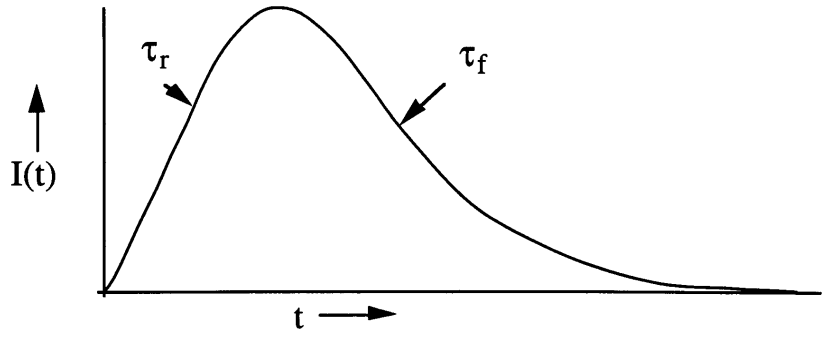
$$I(t) \propto 1 - e^{-t/\tau_r}$$

fall with time constant τ_f

$$I(t) \propto e^{-t/\tau_f}$$

total pulse shape

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



Rise time usually increased substantially by subsequent components in system and variations in path length in large scintillators.

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Properties of some typical organic scintillators

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

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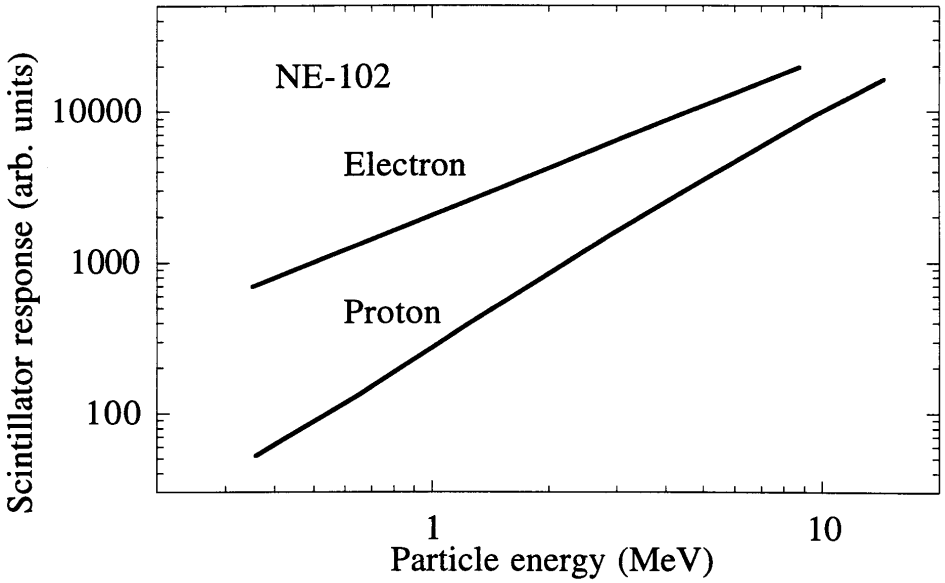
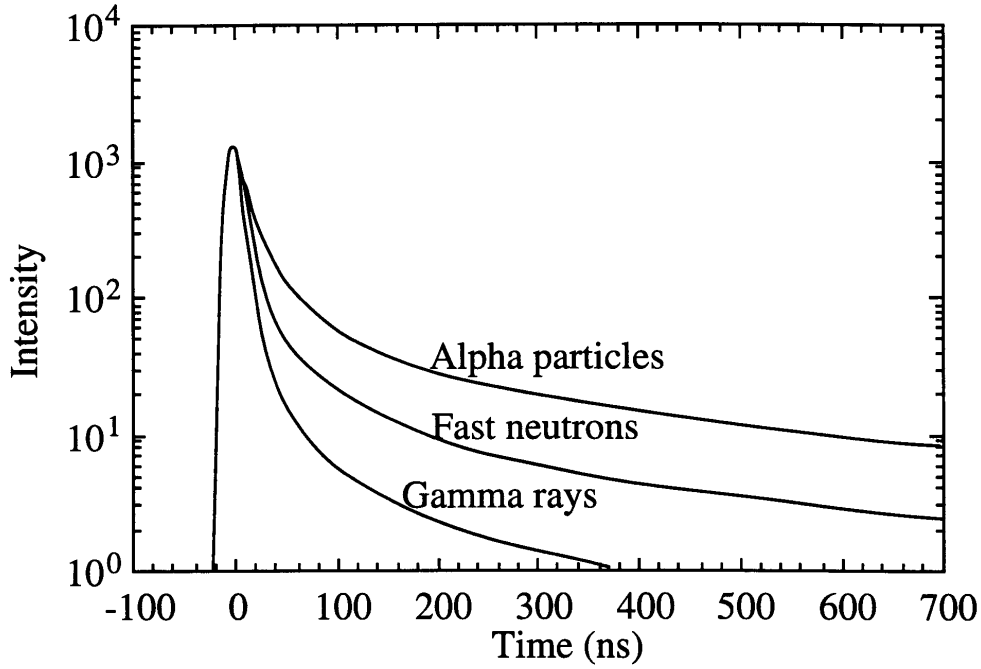
Both the light output and the decay time of organic scintillators depend on the ionization density.



Decay time in stilbene for various particles
(from Bollinger and Thomas)



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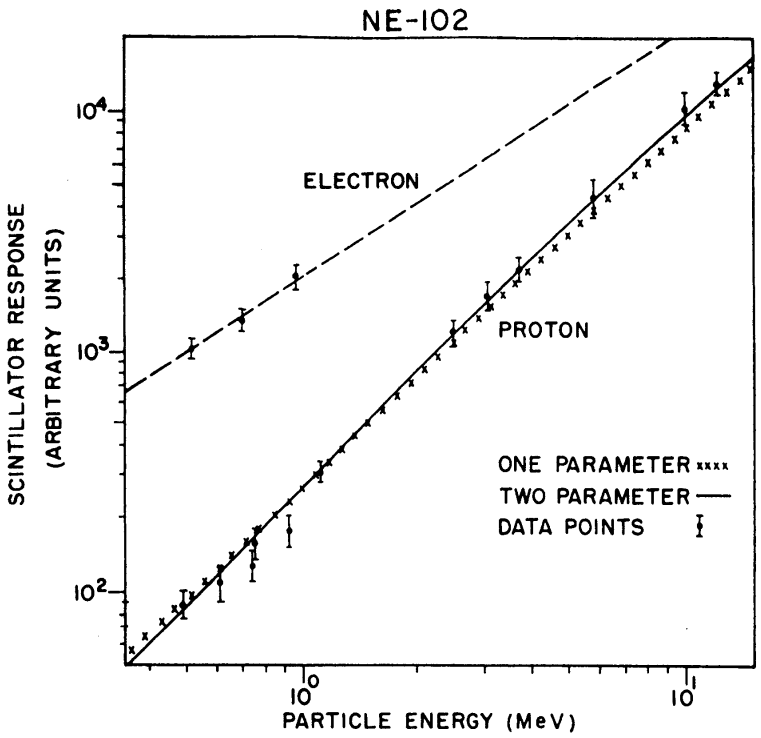
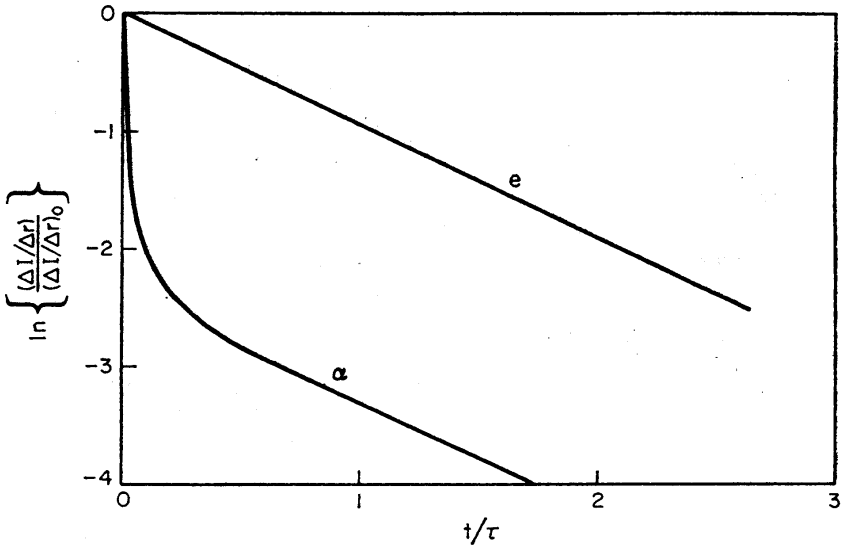
Light yield vs. ionization density



(Craun and Smith)



(Blanc et al.)

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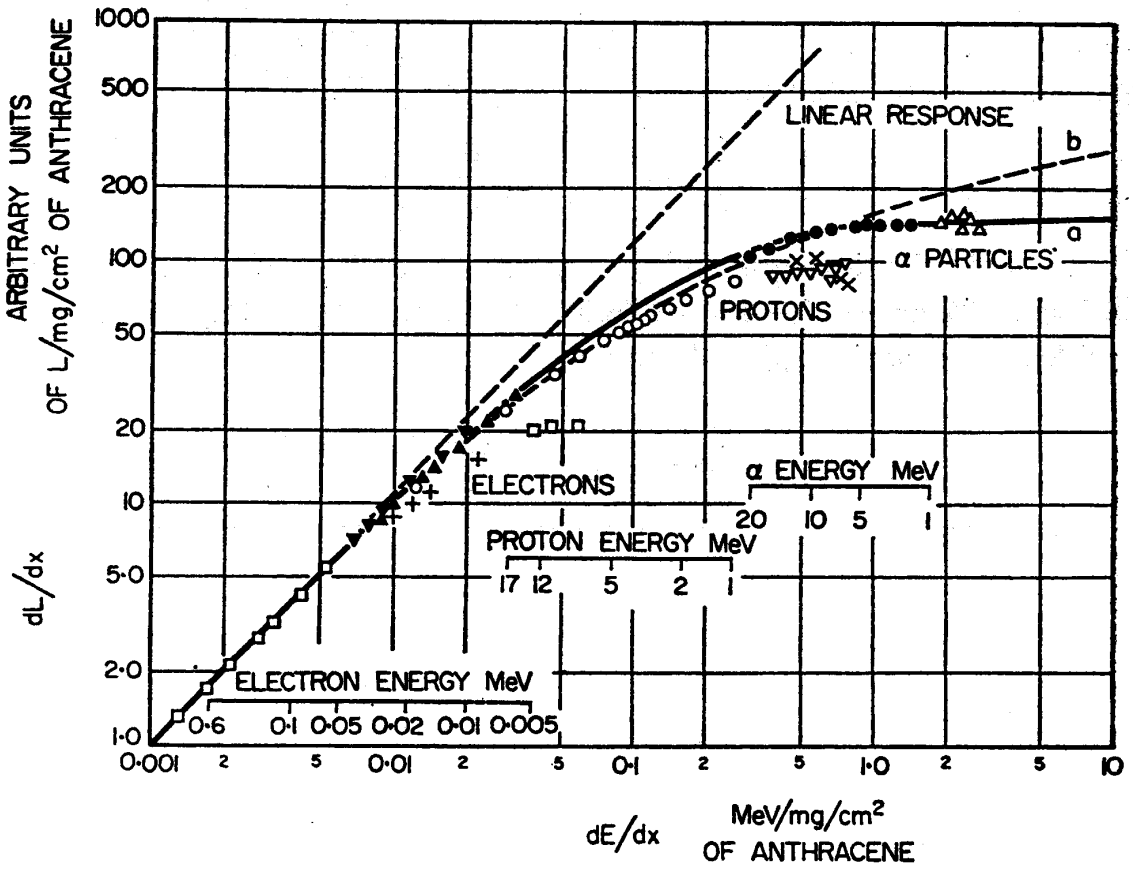

Variation of specific fluorescence dL/dx in anthracene with specific energy loss dE/dx (Brooks, from Birks)

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Birk's Rule

For an ideal scintillator and low ionization density

$$\text{Luminescence} \propto \text{Energy dissipated in scintillator}$$

$$L = SE$$

or, in differential form

$$\frac{dL}{dr} = S\frac{dE}{dr}$$

The specific density of ionized and excited molecules along the particle track is

$$B\frac{dE}{dr}$$

Assume that a portion of the primary excitation is lost at high ionization density (ionization quenching) and introduce a quenching parameter k. Then

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

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

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

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

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The dependence of decay time on ionization density can be used for particle identification.

For example, by utilizing a pulse shaping network that makes the timing of the output pulse dependent on decay time, the particle distribution is transformed into a time distribution that can be digitized directly.

Example: n-γ discrimination

P. Sperr, H. Spieler, M.R. Maier, NIM **116**(1974)55

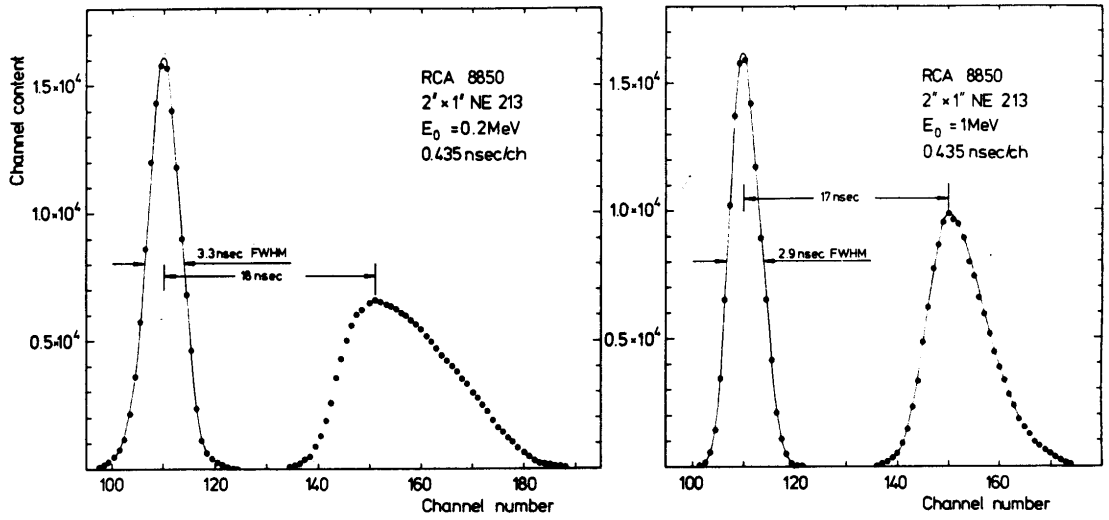

Fig. 5. Neutron–gamma timing distributions with a small scintillator (2″ diam. × 1″) for two threshold energies.

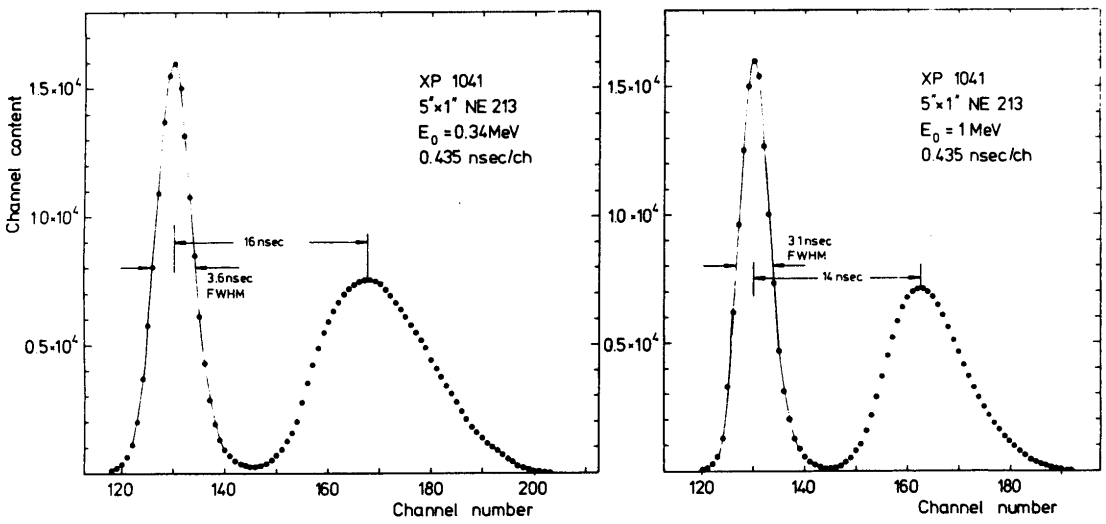

Fig. 6. Neutron–gamma timing distributions with a 5″ diam. × 1″ scintillator for two threshold energies.

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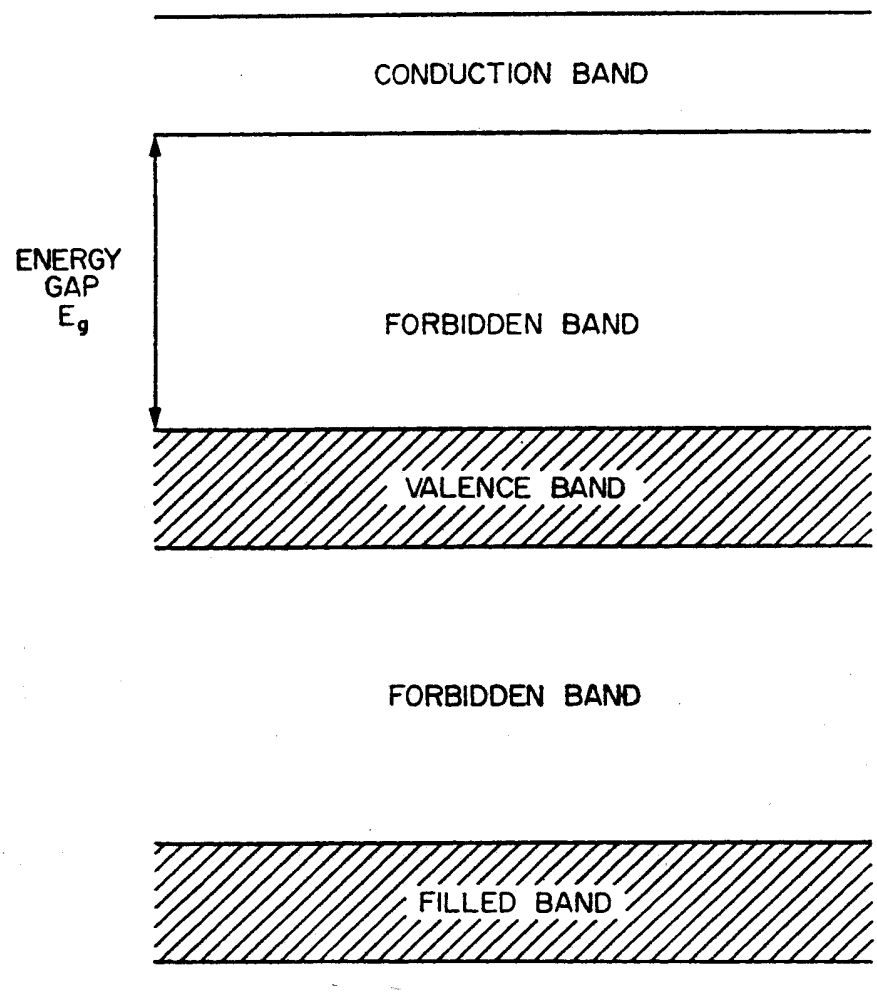
Inorganic Scintillators

Band structure in inorganic crystals



If forbidden band >> kT, no electrons in conduction band.

$\Rightarrow$ Insulator

Radiation excites electron from valence into conduction band, forming an electron-hole pair.

Electrons in conduction band and holes in valence band can move freely throughout crystal.

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For light emission, one must introduce states into the forbidden band, so that

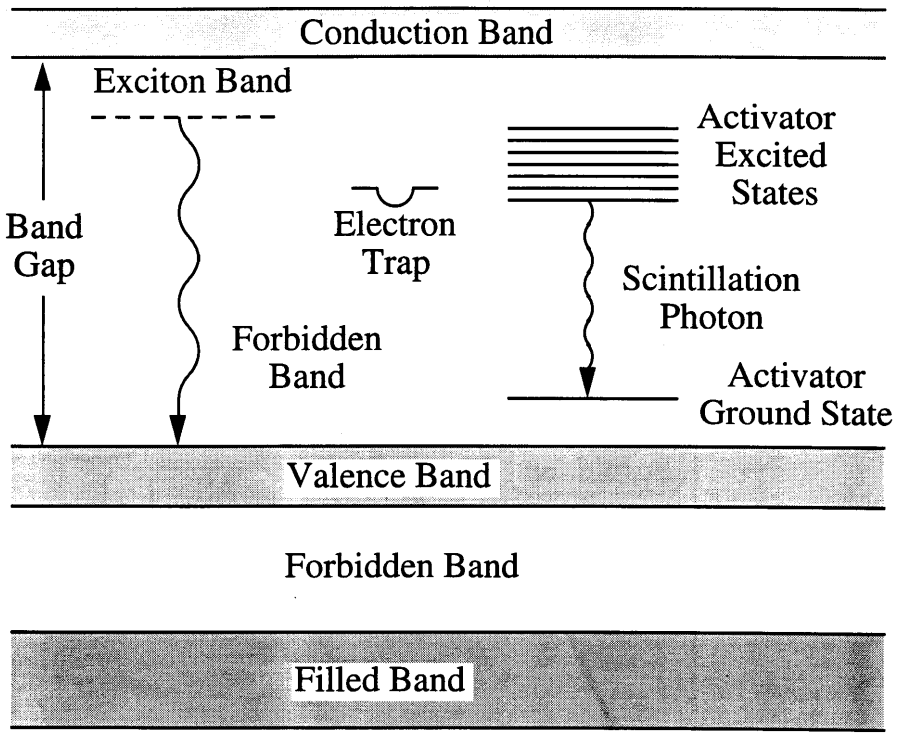
$$E_{emission} < E_g$$

Three mechanisms:

a) excitons (bound electron-hole pair)

b) defects
(interstitial atoms, for example induced by heat treatment)

c) activators



(from Derenzo)

Examples:

cooled NaI: $h^+ + e^- \rightarrow$ exciton $\rightarrow$ phonons + photon

NaI(Tl): $h^+ + Tl^+ \rightarrow Tl2+$ $\quad e^- + Tl^{2+} \rightarrow (Tl^+)^*$

$e^- + Tl^+ \rightarrow Tl^0$ $\quad h^+ + Tl^0 \rightarrow (Tl^+)^*$

$(Tl^+)^* \rightarrow Tl^+ +$ phonons + photon

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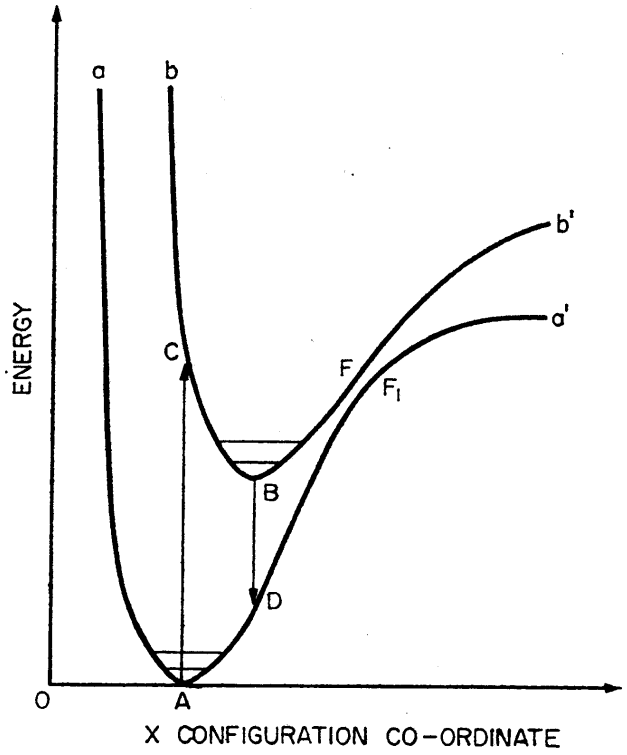
Luminescence vs Quenching



(from Birks)

Excitation:	A → C	(very fast)
thermal equilibration:	C → B	(~10^5 longer)
Photon emission:	B → D	
thermal equilibration:	D → A	

If excited electron reaches F (depending on population of states in minimum B), the transition

$$F \rightarrow F_1$$

can proceed by phonon emission (lattice vibrations),
i.e. without emission of a photon (quenching)

In some crystals, the proximity region F-F_1 is very close to the minimum of the excited state. These crystals are heavily quenched.

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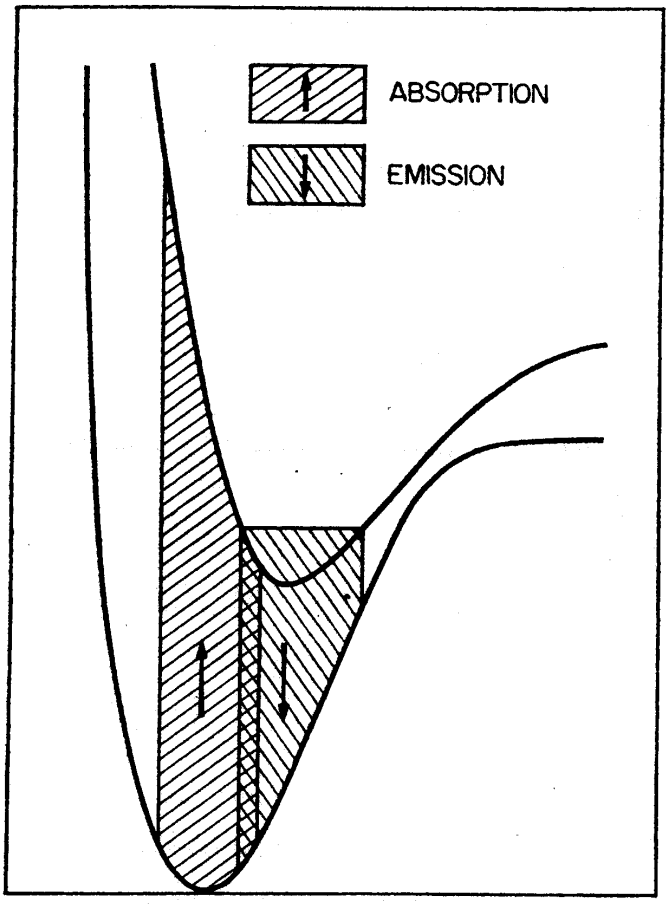
Overlap of absorption and emission spectra



(from Birks)

Width of absorption and emission spectra depend on population of states in the respective minima A and B.

A and B must be sufficiently separated to yield adequate Stokes shift.

At high temperatures the absorption and emission bands broaden, increasing the overlap and the fraction of luminescence photons lost to self-absorption.

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Summary of practical inorganic scintillator materials
(from Derenzo)

Material	Form	λ_{max} (nm)	τ_f (ns)	ρ (g/cm^3)	Photons per MeV
NaI(Tl) (20°C)	crystal	415	230	3.67	38,000
pure NaI (-196°C)	crystal	303	60	3.67	76,000
$Bi_4Ge_3O_{12}$ (20°C)	crystal	480	300	7.13	8,200
$Bi_4Ge_3O_{12}$ (-100°C)	crystal	480	2000	7.13	24,000
CsI(Na)	crystal	420	630	4.51	39,000
CsI(Tl)	crystal	540	800	4.51	60,000
CsI (pure)	crystal	315	16	4.51	2,300
CsF	crystal	390	2	4.64	2,500
BaF_2 (slow)	crystal	310	630	4.9	10,000
BaF_2 (fast)	crystal	220	0.8	4.9	1,800
Gd_2SiO_5(Ce)	crystal	440	60	6.71	10,000
$CdWO_4$	crystal	530	15000	7.9	7,000
$CaWO_4$	crystal	430	6000	6.1	6,000
CeF_3	crystal	340	27	6.16	4,400
$PbWO_4$	crystal	460	2, 10, 38	8.2	500
Lu_2SiO_5(Ce)	crystal	420	40	7.4	30,000
$YAlO_3$(Ce)	crystal	390	31	5.35	19,700
Y_2SiO_5(Ce)	crystal	420	70	2.70	45,000

Note the wide range of decay times τ_f, from 0.8 ns in BaF_2 to 15 μs in $CdWO_4$.

Some materials also show multiple emissions (BaF_2, $PbWO_4$).

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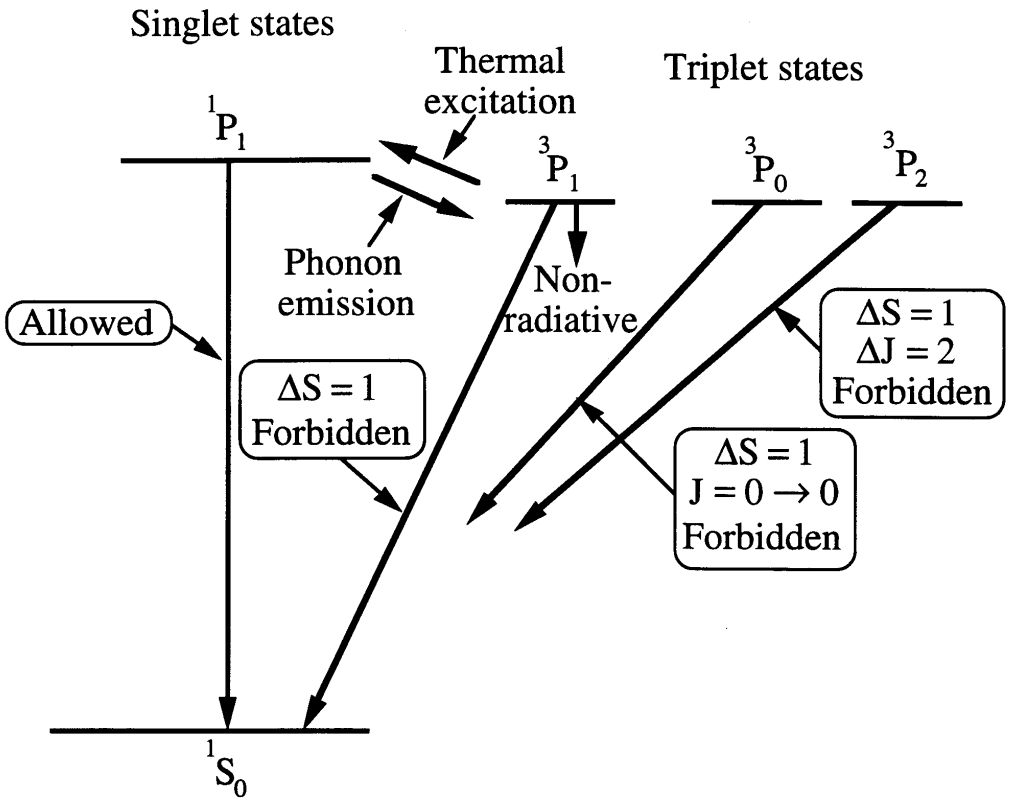
Scintillators with Tl, Bi, etc. decay slowly due to “forbidden” transitions to the ground state:



(from Derenzo)

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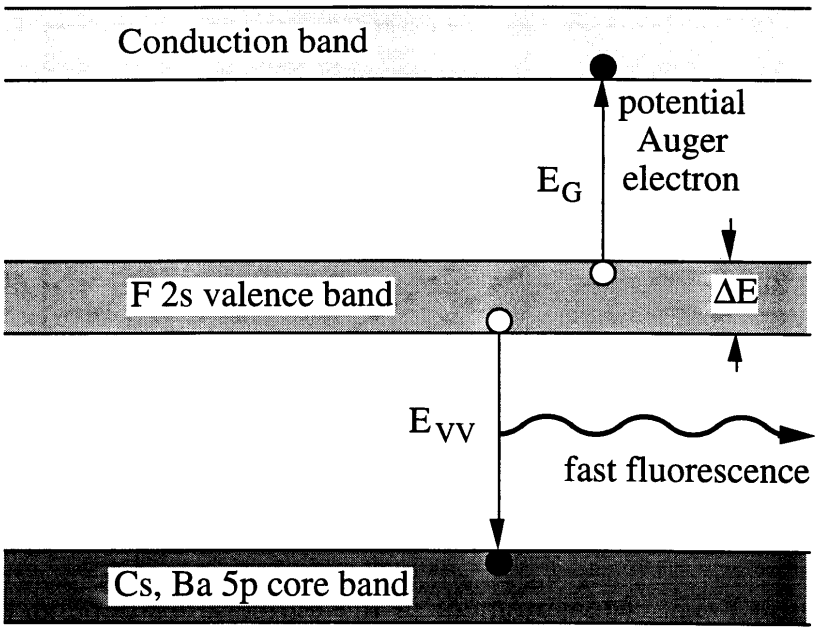
The very fast transitions in BaF_2 and CsF are due to an intermediate transition between the valence and core bands.



$E_{vv} < E_g$ fast fluorescence

$E_{vv} > E_g$ emission of Auger electron

(energy released in the transition from the valence to the core band does not go into photon emission, but into emission of an electron to the conduction band)

Competition between photon emission and Auger effect narrows the range of scintillators with fast decays:

If E_{vv} is low: longer wavelength emission, longer decay time

If E_{vv} is high: Auger emission, no scintillation light

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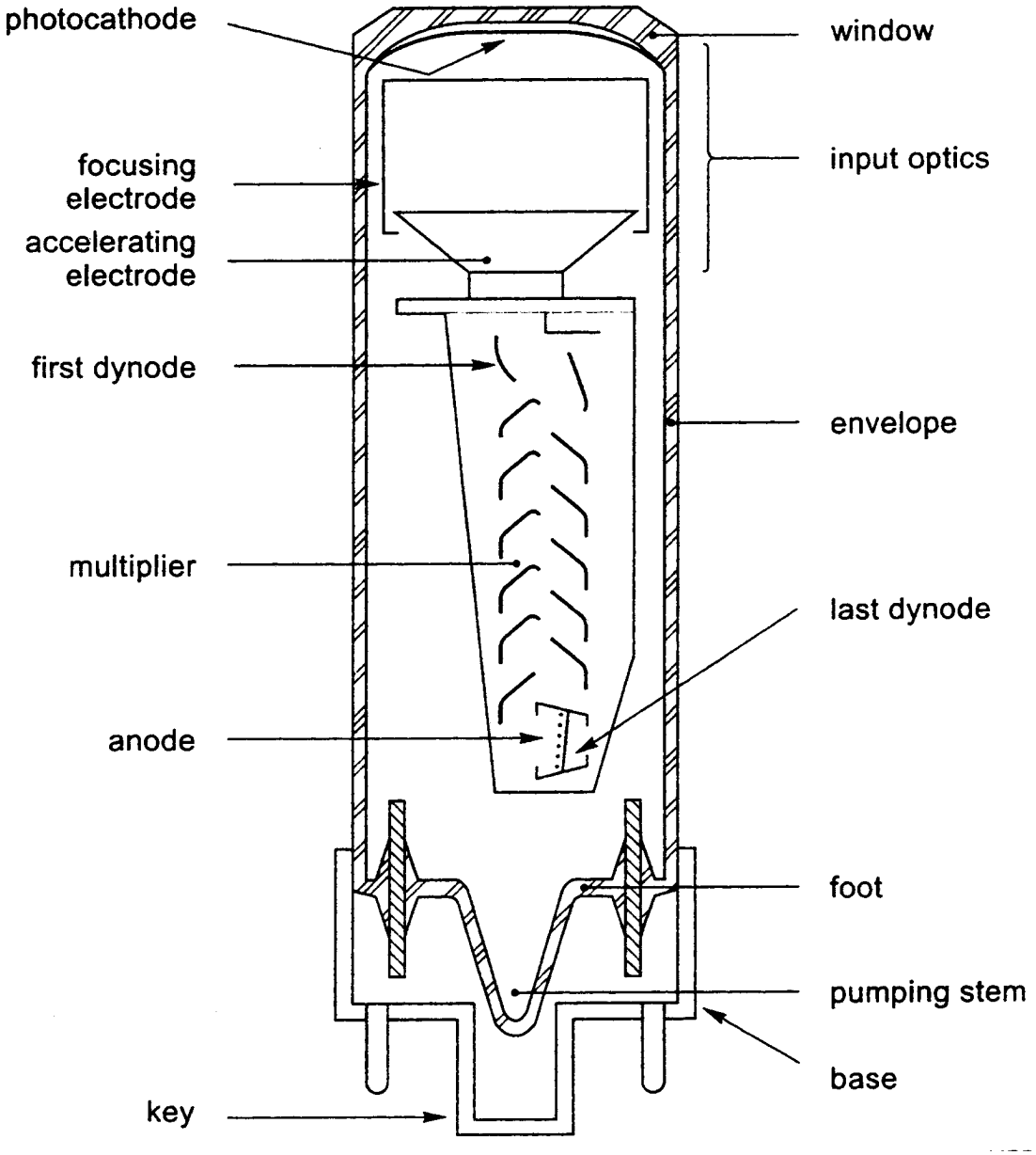
Conversion of Scintillation Light to Electrical Signal

Most Common Device:

Photomultiplier Tube



(from *Photomultiplier Tubes*, Philips Photonics)

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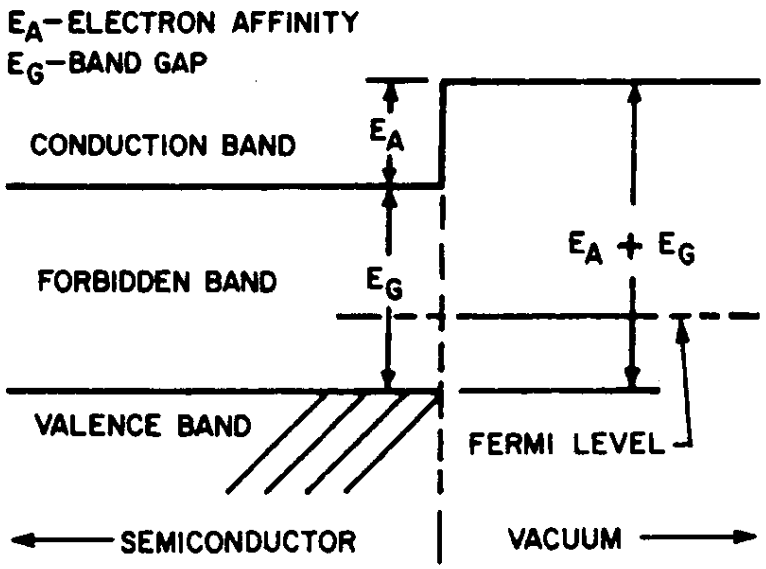
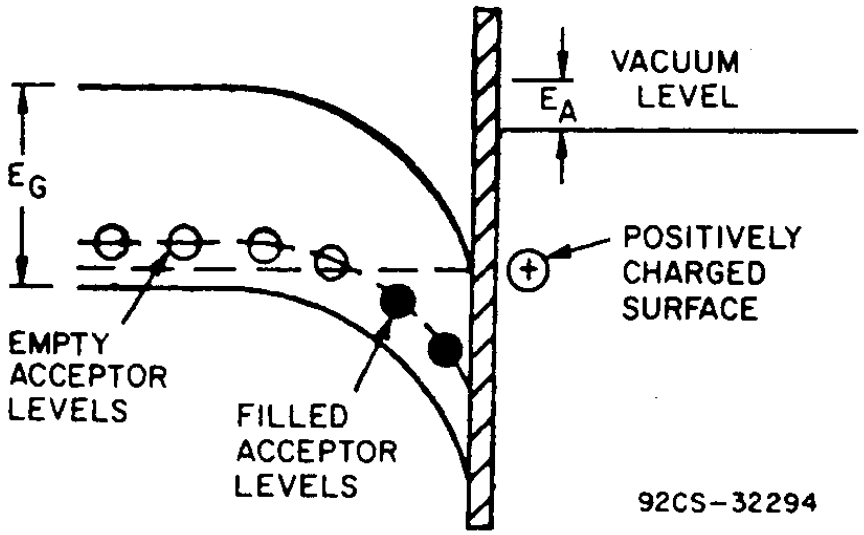
Photocathodes

Band structure in “standard” photocathode



Band structure in “negative electron affinity” photocathode



(from *Photomultiplier Handbook*, Burle Industries)

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Summary of Photocathode Materials

(from Derenzo)

Cathode type	Composition	Peak Q.E.	Peak λ
S1	AgOCs	0.4%	800 nm
S10	BiAgOCs	7%	420 nm
S11	CS_3SbO	21%	390 nm
S20 (multi-alkali)	Na_2KSbCs	22%	380 nm
Bialkali	K_2CsSb	27%	380 nm
Bialkali (high temp)	Na_2KSb	21%	360nm
	KCsRbSb	24%	440 nm
Bialkali	RbCsSb	25%	450 nm
Solar blind*	CeTe	18%	200 nm
Solar blind**	CsI	15%	135nm

* Q.E. > 0.1% above 320 nm
** Q.E. > 0.1% above 210 nm

Maximum quantum efficiency n above table is 27%.
Is this reasonable?

- no electric field within photocathode to direct electrons to emitting surface
- photoelectrons initially emitted isotropically
  - $\Rightarrow$ ½ directed toward faceplate
  - $\Rightarrow$ ½ directed toward dynode structure
- transmission losses (bialkali photocathodes 40% transmissive

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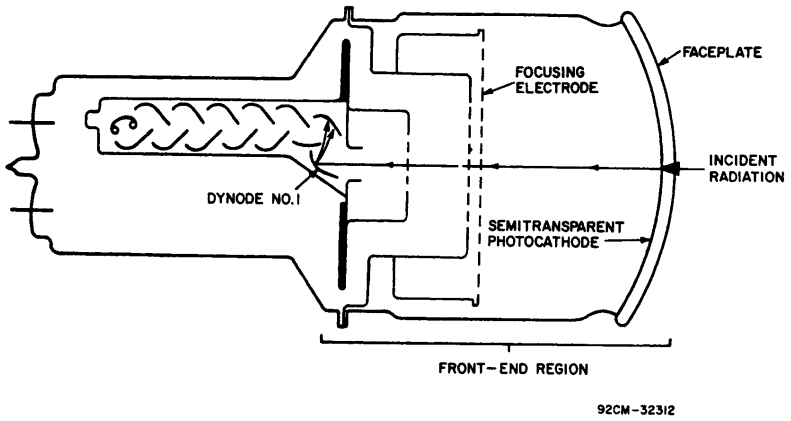

Fig. 26 - Photomultiplier design with curved faceplate and in-line dynode structure to provide a minimum transit time and transit-time spread.

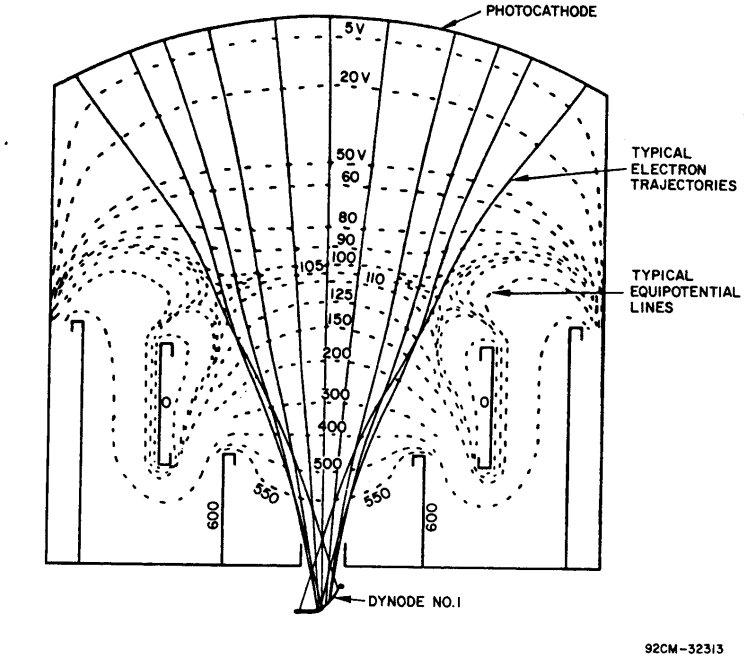

Fig. 27 - Cross section of a photomultiplier showing equipotential lines and electron trajectories that were plotted by computer.

(from *Photomultiplier Handbook*, Burle Industries)

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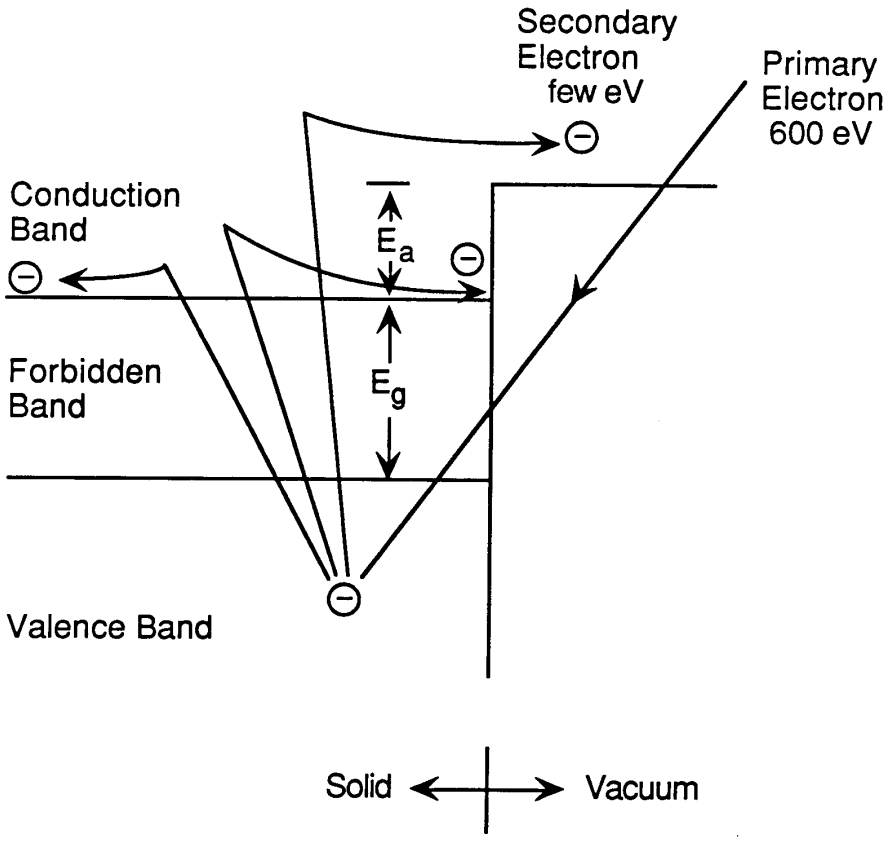
Secondary Emission in Dynodes



BeO(Cs)

$\delta \sim 8$

(D. Persyk)

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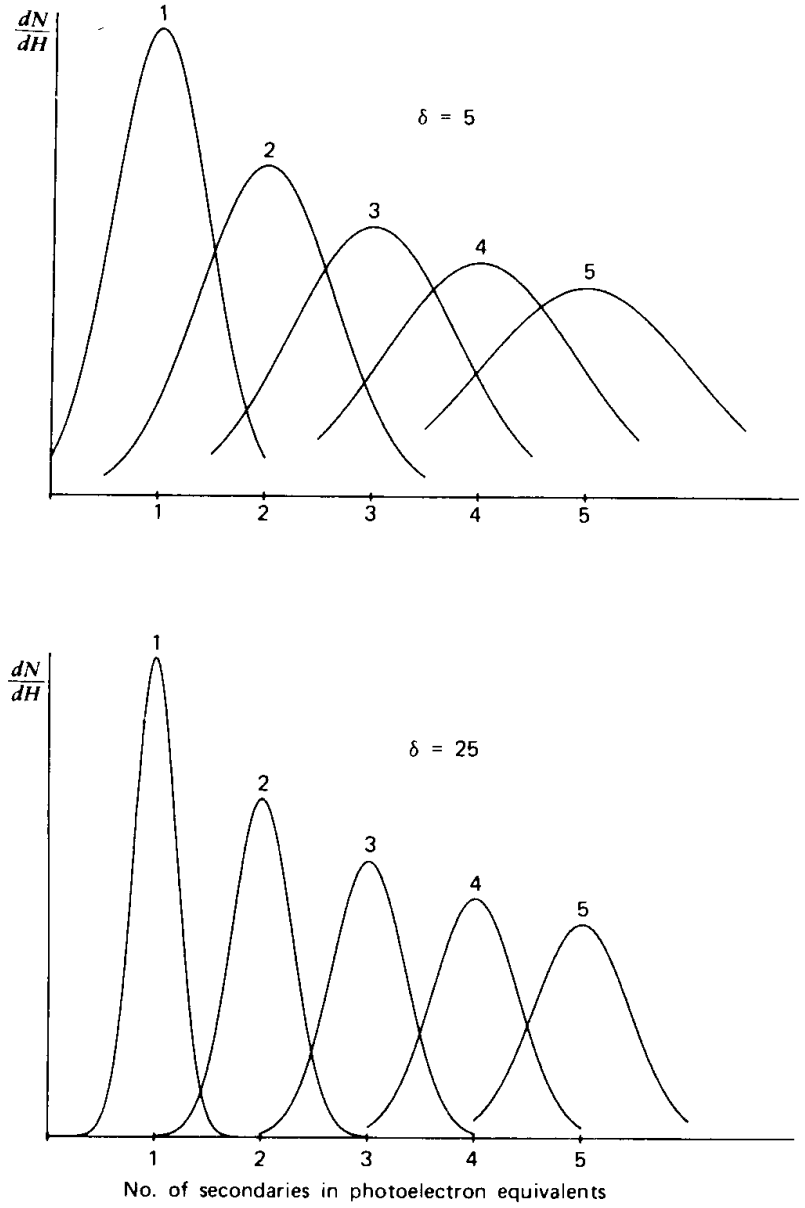
Desirable to obtain high secondary emission yields to reduce fluctuations (spectral broadening).

Typical dynode materials: Be0(Cs), Cs_3Sb, MgO

Negative electron affinity materials can also be used in dynodes (e.g. GaP(Cs), bottom distributions) – but more difficult to fabricate.



(from Knoll)

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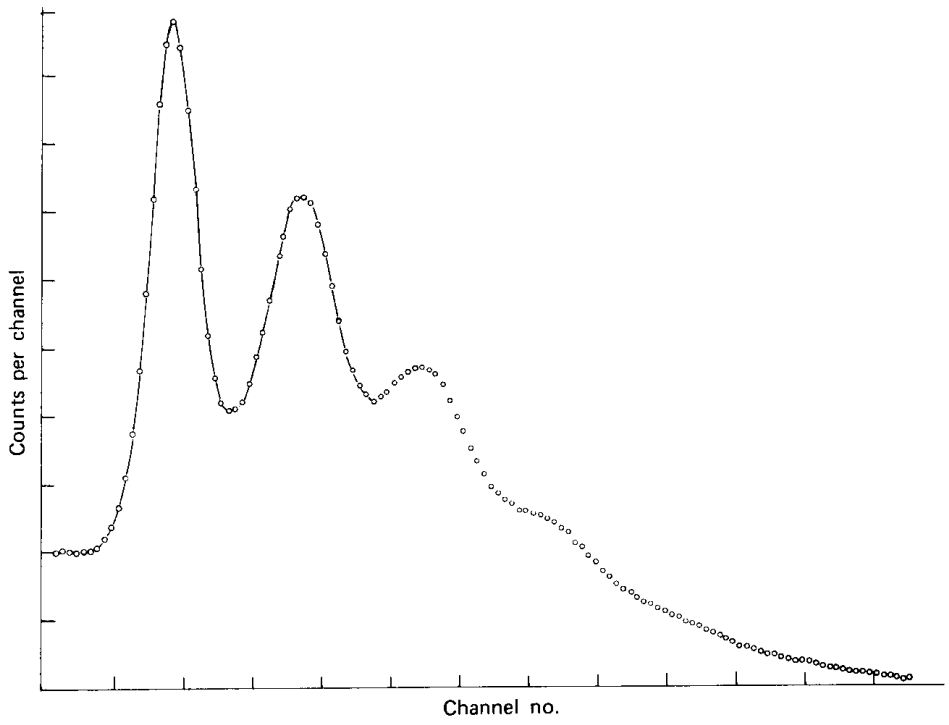
High emission dynodes allow resolution of single photoelectrons



(from Knoll)

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Many different dynode configurations have been developed to reduce size or improve gain, uniformity over large photocathode diameters, transit time and transit time spread.

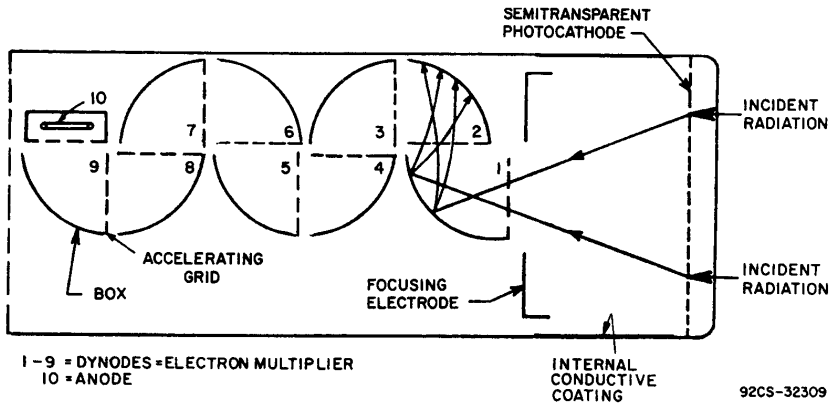

Fig. 23 - The box-and-grid multiplier structure.

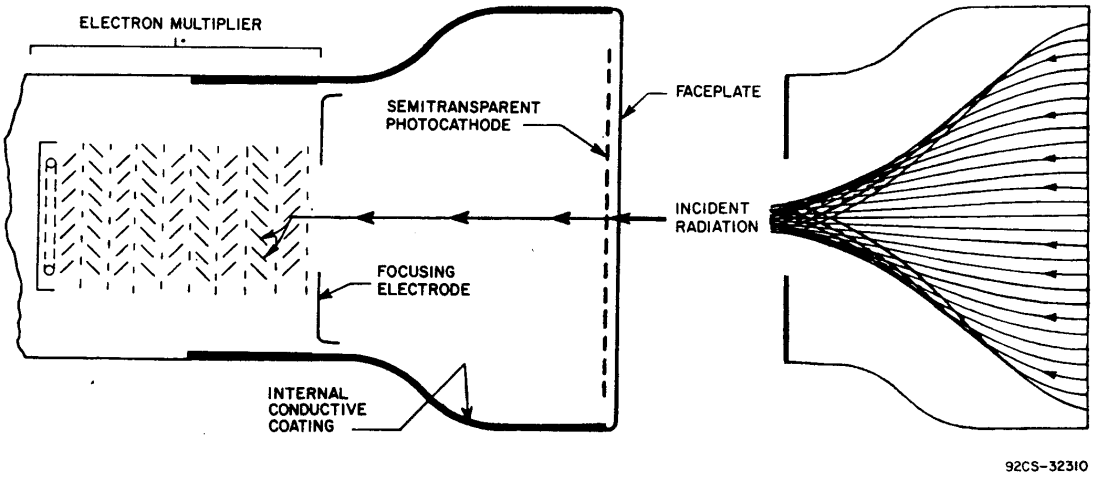

Fig. 24 - The venetian-blind multiplier structure.

(from *Photomultiplier Handbook*, Burle Industries)

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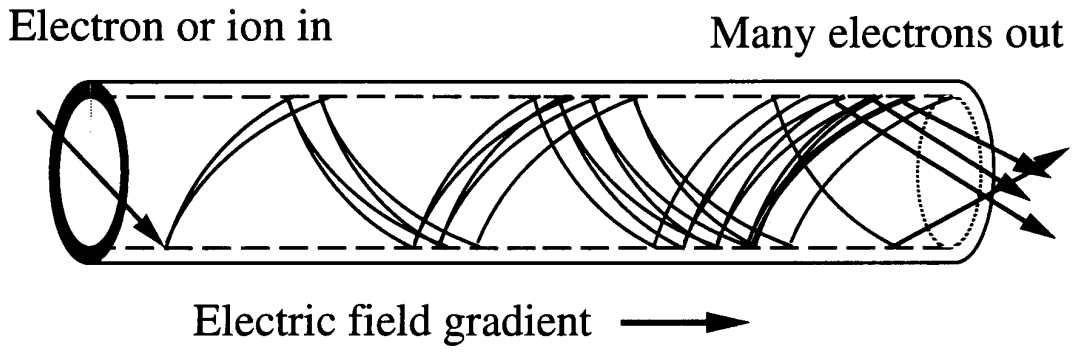
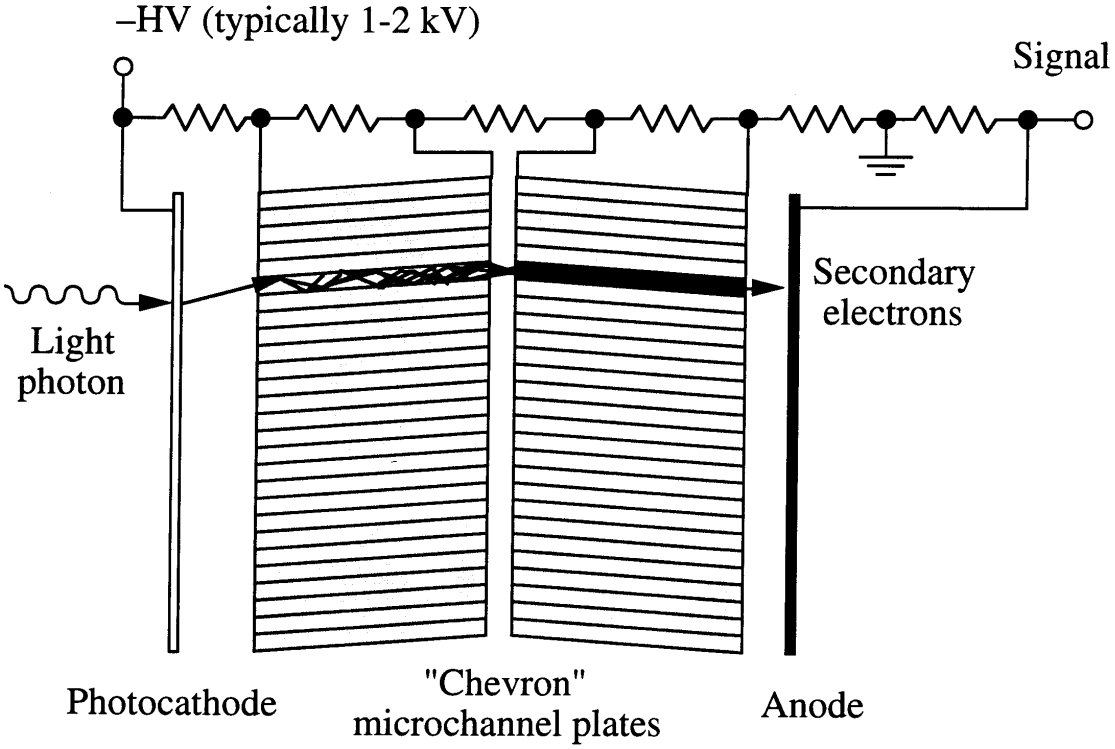
Continuous multiplier structures

Channel electron multiplier



(from Derenzo)

Can be combined in “microchannel plates”



(from Derenzo)

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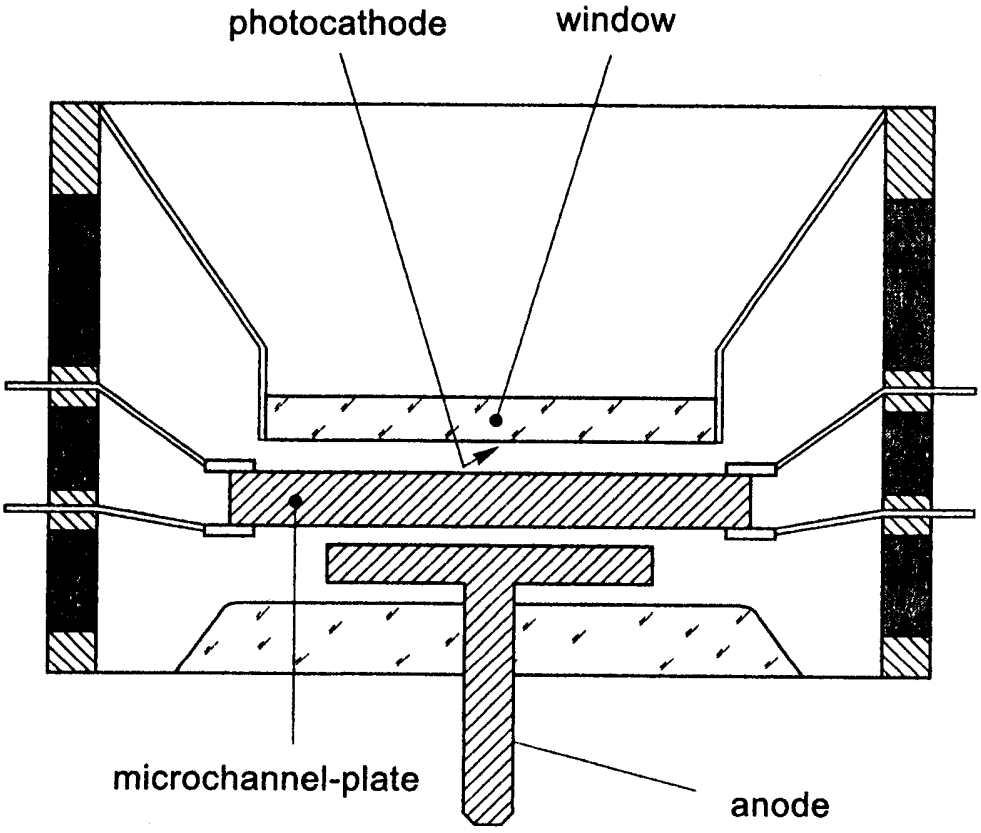
Microchannel plates can be utilized in photomultipliers for ultra-fast timing with low time-dispersion.



(from *Photomultiplier Tubes*, Philips Photonics)

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Signal Evolution

1. energy is absorbed in scintillator
2. population of states that emit photons

   number of radiative states

   $N_0 = E_{abs}/\varepsilon_i$

   E_{abs} energy absorbed in scintillator

   ε_i energy required to produce 1 photon

3. population of radiative states decays

   $\Rightarrow$ rate of photon emission

$$\frac{dN_{ph}}{dt} \equiv n_{ph}(t) = \frac{N_0}{\tau} e^{-t/\tau}$$

   Total number of photons emitted after time T

$$N_{ph}(T) = \int_0^T n_{ph}(t)dt = N_0(1 - e^{-T/\tau})$$

4. photons absorbed in photocathode, producing photoelectrons

$$n_{pe}(t) = QE \cdot n_{ph}(t) = QE \cdot N_0 e^{-t/\tau}$$

5. photoelectrons transported through gain structure (dynodes in PMT) multiplied by G

   $\Rightarrow$ electric current at anode

$$I_{anode}(t) = G \cdot QE \cdot N_0 e^{-t/\tau}$$

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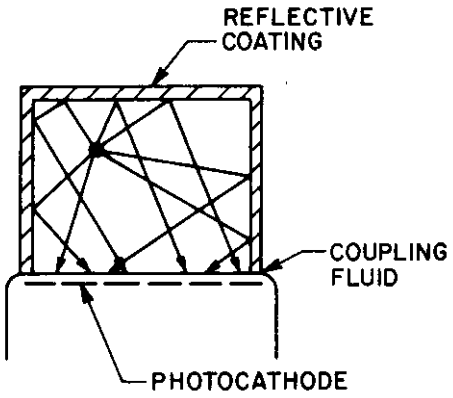
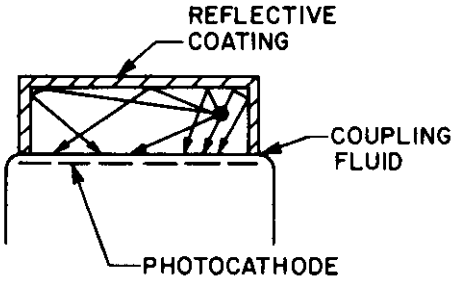
How much of this signal is actually obtained?

1. Scintillator is coupled to PMT at one surface





(from *Photomultiplier Handbook*, Burle Industries)

Scintillation light is emitted isotropically.

Depending on the geometry, at least half of emitted photons must be reflected one or more times to reach the faceplate of the photodetector.

Light losses due to

a) absorption in crystal

b) reflection losses

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Scintillation crystals invariably optically denser than air

examples:	NaI(Tl)	n= 1.85
	CsI(Tl)	n= 1.795
	$CdWO_4$	n= 2.2 – 2.3
	BGO	n= 2.152
	NE102	n= 1.581 (plastic)
	NE213	n= 1.508 (org. liquid)
	air	n= 1

$\Rightarrow$ Requirement for total reflection

$$\sin\alpha \geq \frac{1}{n_{xtal}}$$

Light incident within an angle α from normal incidence will leave the crystal.

example $n_{xtal} = 1.5 \Rightarrow \alpha = 42°$

External reflective layers can improve this situation (see following discussion of light-guides).

2. Upon reaching the faceplate, light can be either transmitted or reflected

refractive index of faceplate
(borosilicate glass or fused silica) $n_{fp} \approx 1.5$

Important to avoid air-gap
(use optical grease to provide index match)

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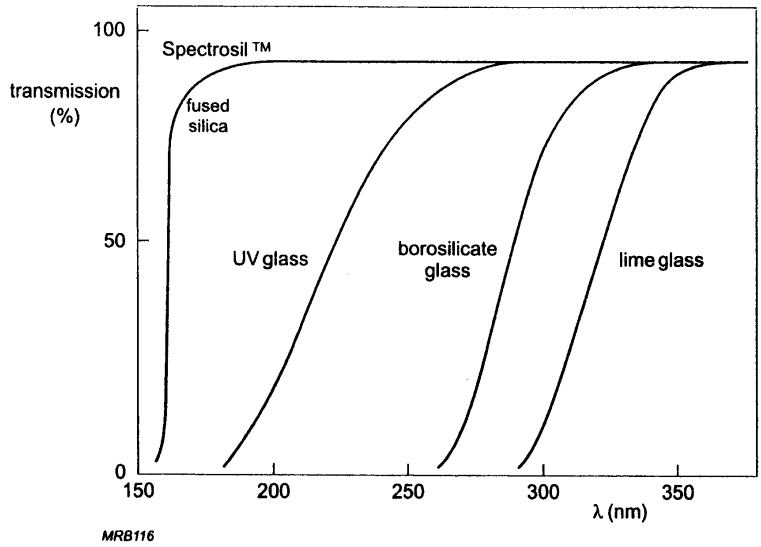
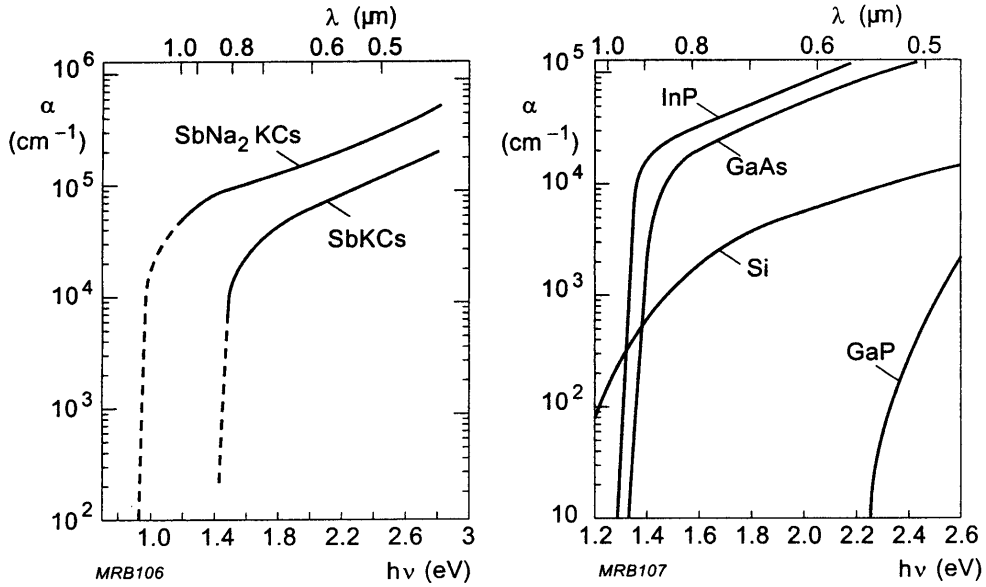
3. photons must be transmitted through the faceplate



(from *Photomultiplier Tubes*, Philips Photonics)

4. Photons must be absorbed in the photocathode



(from *Photomultiplier Tubes*, Philips Photonics)

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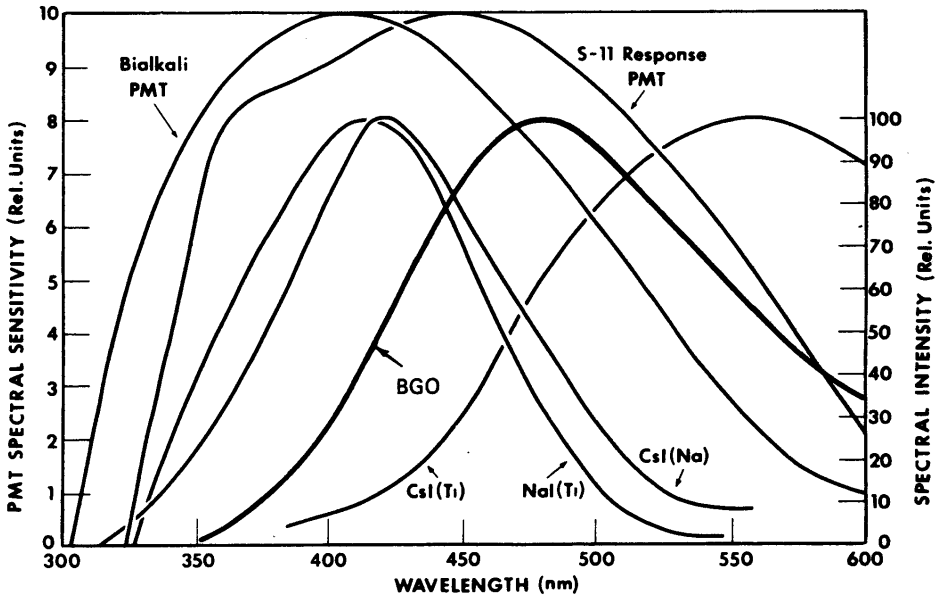
5. Photoelectrons must traverse the photocathode and reach the first dynode to be multiplied.

It is important that the emission spectrum of the scintillator, the transmission through the faceplate and the absorption in the photocathode are matched.



(from Knoll)

Note that for short wavelength scintillators (for example the fast component of BaF_2 at 220 nm) conventional borosilicate faceplates are very inefficient – use fused silica for extended UV response.

Typical NaI(Tl) system (from Derenzo)

511 keV gamma ray

⇓

25000 photons in scintillator

⇓

15000 photons at photocathode

⇓

3000 photoelectrons at first dynode

⇓

$3 \cdot 10^9$ electrons at anode

2 mA peak current

Resolution of energy measurement determined by statistical variance of produced signal quanta.

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

Resolution determined by smallest number of quanta in chain, i.e. number of photoelectrons arriving at first dynode.

In this example

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{3000}} = \text{ 2\% r.m.s. } = \text{ 5\% FWHM}$$

Typically 7 – 8% obtained, due to non-uniformity of light collection and gain.

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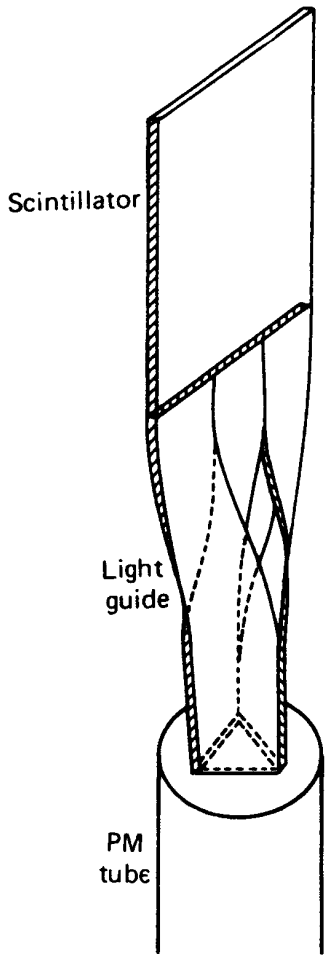
The PMT is often coupled to the scintillator through a light guide



(from Knoll)

Match geometry of scintillator to photodetector.

Spatial separation of scintillator and detector

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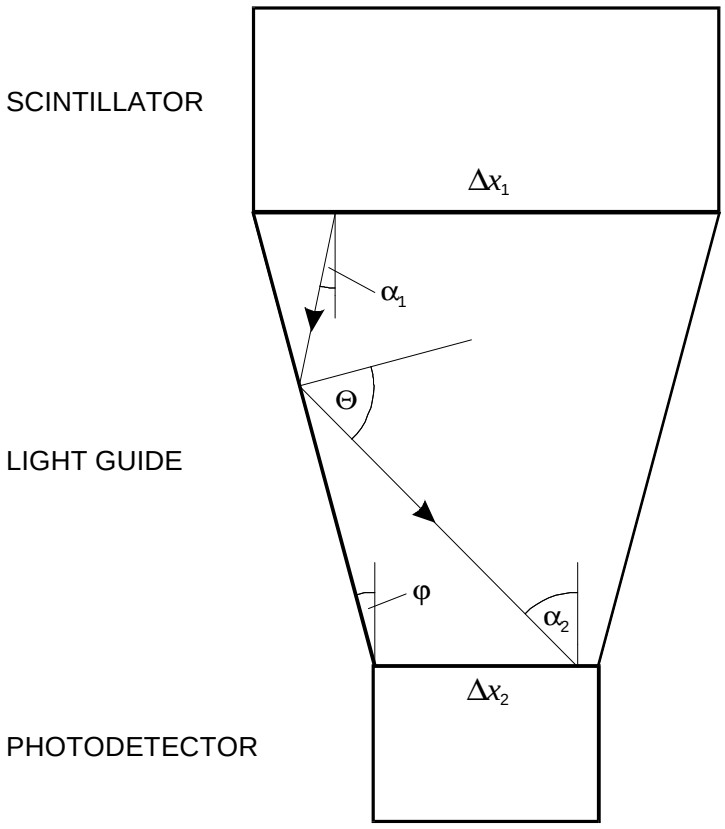
Light Transmission Through Light Guides

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)



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1. Total reflection.

For rays to be reflected from the surface of the light guide the incident angle

$$\sin\Theta \geq \frac{n_{ext}}{n}$$

where n is the refractive index of the light guide and n_{ext} that of the external medium. When the external medium is air (n_{ext}= 1)

$$\sin\Theta \geq \frac{1}{n}$$

If the light guide is tapered with an angle φ, a ray at the limit of total reflection will impinge on the output face at an angle

$$\frac{\pi}{2} + \varphi - \Theta$$

This is the maximum angle at the light guide output. Since the maximum reflection angle in the light guide is $\pi/2$, the minimum angle of reflected rays at the exit is φ, whereas direct rays can impinge with zero angle.

2. Conservation of phase space

(see D. Marcuse, BSTJ **45** (1966) 743, Applied Optics **10/3** (1971) 494)

The trajectories of photons can be described analogously to particles whose position and slope are described as a point in phase space with the coordinates x and p. For photons these canonically conjugate variables are the the transverse coordinates of the photon ray and its angle. In two dimensions (adopted here for simplicity) the variables are the transverse coordinate x and the quantity

$$p = n\sin\alpha$$

where n is the refractive index of the medium and α is the angular divergence of the photon beam.

At the entrance of the light guide the transverse dimension is Δx_1, so if the maximum angle of a light ray is α_1, the volume element in phase space is

$$\Delta x_1 \Delta p_1 = 2\Delta x_1 n \sin\alpha_1$$

Correspondingly, at the output

$$\Delta x_2 \Delta p_2 = 2\Delta x_2 n \sin\alpha_2$$

Since the volume element must be conserved

$$\Delta x_1 \Delta p_1 = \Delta x_2 \Delta p_2 \ ,$$

a maximum acceptance angle α_2 at the output means that at the input only rays within an entry angle

$$\sin\alpha_1 = \frac{\Delta x_2}{\Delta x_1} \sin\alpha_2$$

can propagate through the light guide.

- Note that even if total reflection obtained over all angles ($n = \infty$), a light guide with $\Delta x_1 >> \Delta x_2$ would incur substantial light loss because of limitation of the acceptance angle.

As shown above, total internal reflection allows a maximum angle of

$$\alpha_2 = \frac{\pi}{2} + \varphi - \Theta$$

so

$$\sin\alpha_2 = \sin\left(\frac{\pi}{2} + \varphi - \Theta\right) = \cos(\Theta - \varphi) = \sqrt{1 - \sin^2(\Theta - \varphi)}$$

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For simplification, assume that the lightguide is only slightly tapered

$$\sin\alpha_2 \approx \sqrt{1-\sin^2\Theta} = \sqrt{1-\frac{1}{n^2}}$$

($\varphi << \Theta$). Then

Thus, the maximum acceptance angle imposed by phase space at the input of the light guide

$$\sin\alpha_1 = \frac{\Delta x_2}{\Delta x_1}\sin\alpha_2 = \frac{\Delta x_2}{\Delta x_1}\sqrt{1-\frac{1}{n^2}}$$

Typical lightguide materials have a refractive index $n \approx 1.5$, so even for equal dimensions Δx_1 and Δx_2

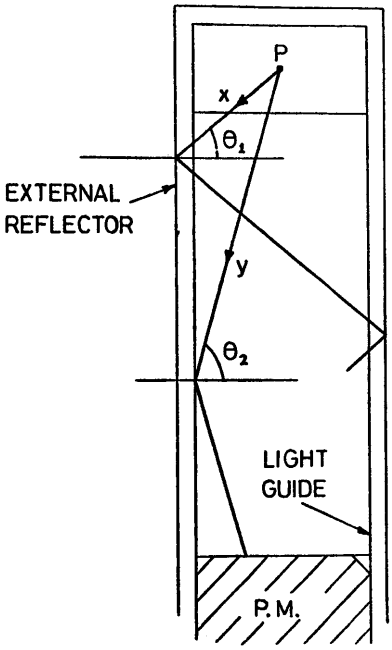
$$\sin\alpha_1 = \sqrt{1-\frac{1}{n^2}} = 0.75$$

Translated to three dimensions, conservation of phase space means that the flux of photons per unit area and per unit solid angle is constant throughout a given medium. Consequently, no optical coupling scheme relying on reflection or diffraction alone can transmit photons from a large source to a small detector with full efficiency.

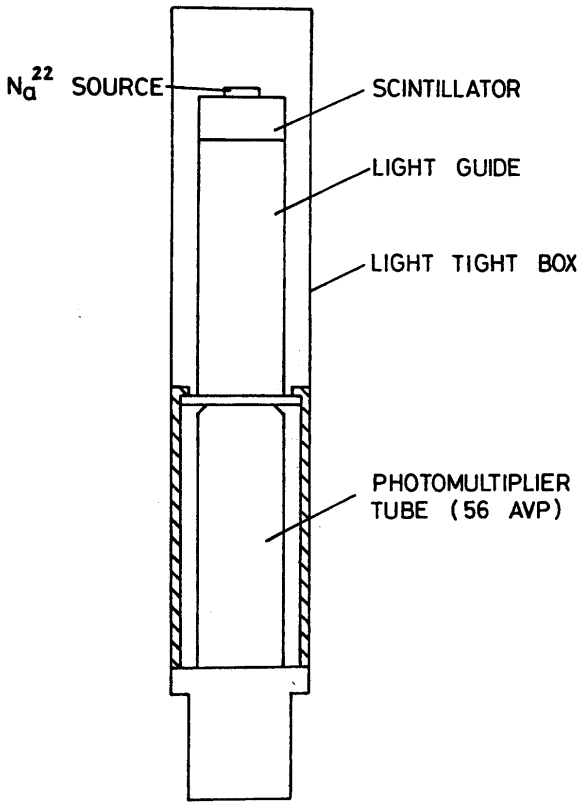
This limitation can be overcome by wavelength shifters, that absorb the incident light and re-emit photons, thereby redefining the phase space element.

Implementation of Light Guides

ref: Kilvington et al., NIM **80** (1970) 177



Where the condition for total reflection is not met, an external reflector can help.



Experimental arrangement

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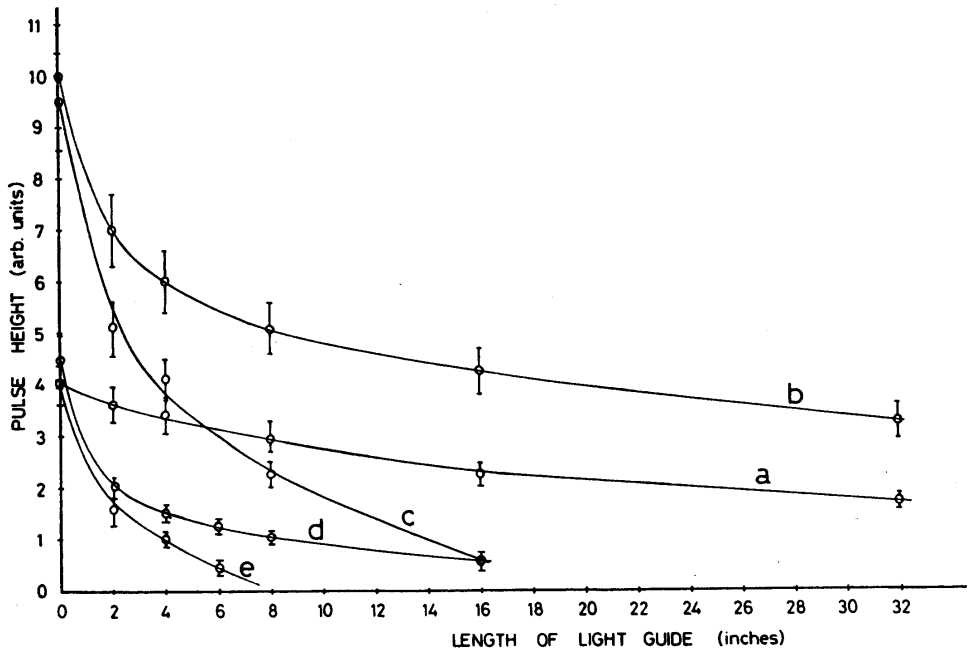
Variation of pulse height with length of light guide



a) Total internal reflection only

b) Total internal reflection with reflective coating

either... aluminum foil
aluminized mylar
transparent mylar painted with reflective paint

c) Surface of light guide coated with reflective paint

d) Specular reflector without light guide

e) Diffuse reflector without light guide

Although peak light output can be improved by reflective coatings, this only obtains with short light guides.

Critical that surface of light guide be smooth.

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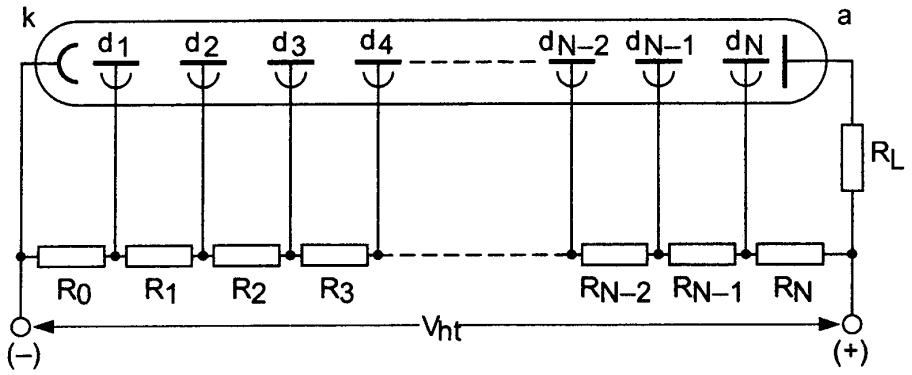
Operational aspects of using PMTs

Electron multiplication at dynodes depends on potential between successive dynodes.

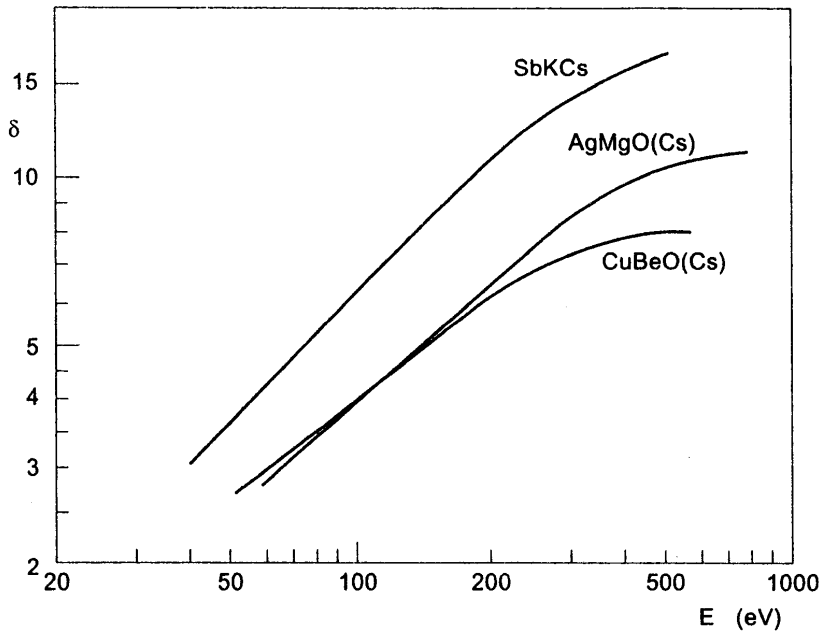
Potential distribution commonly set by resistive divider.



(from *Photomultiplier Tubes*, Philips Photonics)

Secondary electrons are emitted with low energy and accelerated by potential difference between dynodes.

Secondary emission coefficients of commonly used dynode materials vs. incident electron energy:



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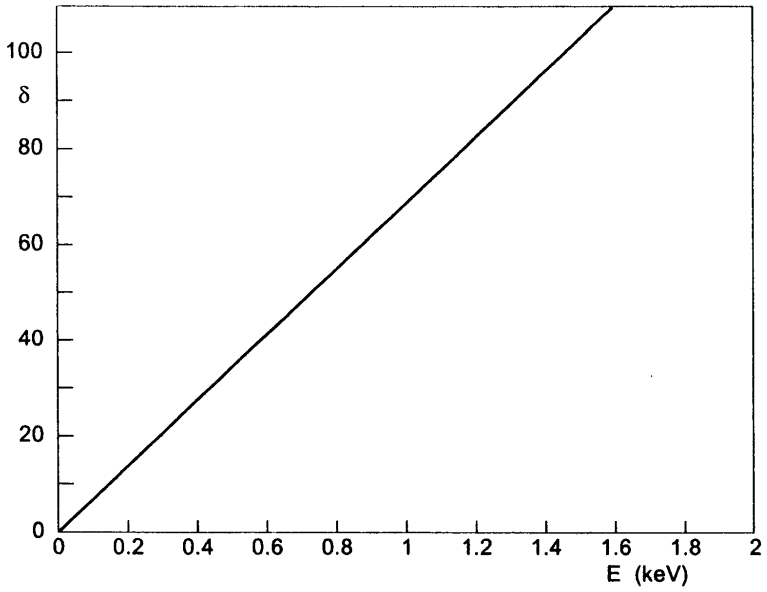
The gain of GaP(Cs) NEA dynodes does not exhibit the gain saturation of conventional materials.



(from *Photomultiplier Tubes*, Philips Photonics)

Advantageous especially at first dynode to improve gain distribution of multiplication chain.

Typically, PMTs are operated with total supply voltages of 2 kV.

8 to 14 stages (number of dynodes) are common, with 100 to 150 V between dynodes.

The potential between the photocathode and the first dynode is typically 4 times as large to improve the collection efficiency and the gain in the first stage.

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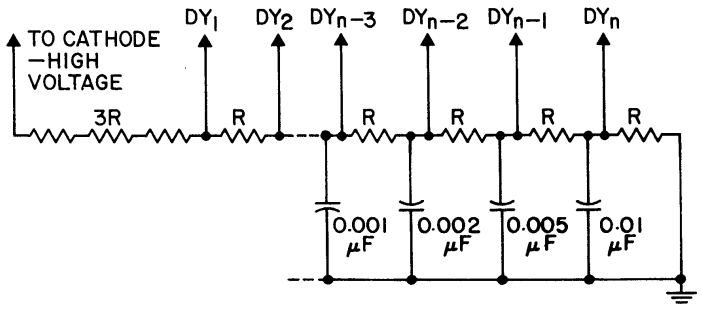
Peak currents of anode pulses can be as high as 20 mA.

If the voltage divider is not capable of providing this current, the acceleration potential will “sag”, leading to non-linearity. (Note that total gain changes with *n*-th power of voltage!)

Necessary to provide capacitors as “charge reservoirs”:



(from *Burle Photomultiplier Handbook*)

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

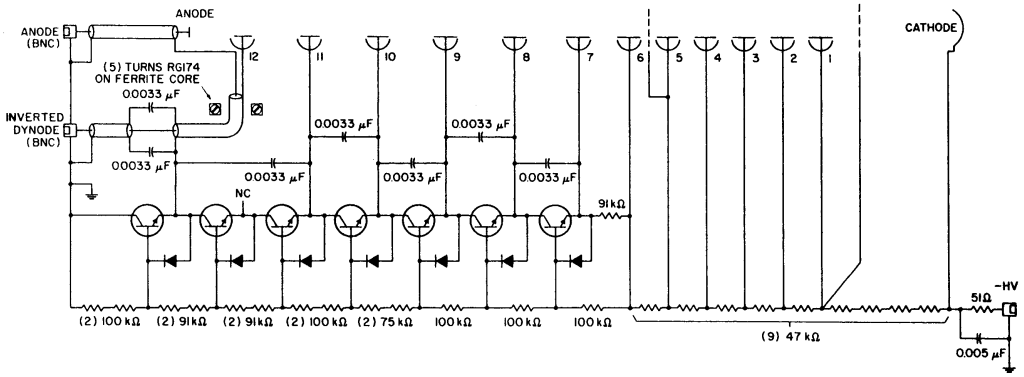
The average current at a gamma rate of n s^{-1} is

$$\langle I \rangle = n \cdot N_{el,\text{anode}} \cdot q_e$$

Using the NaI(Tl) example used before, for which each 511 keV gamma produced $3 \cdot 10^9$ electrons at the anode, the average signal current at a rate of 10^5 s^{-1} is 48 μA.

Thus, the standing current in the resistive divider should be 1 mA or more, leading to a power (heat) dissipation of 2 W at 2 kV total supply voltage.

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.



(from *Burle Photomultiplier Handbook*)

Although the polarity of the supply voltage is fixed, i.e. the anode must be more positive than the cathode, one can choose whether the anode or cathode is at ground potential.

Although grounding the cathode is widespread, oparation with the anode at ground potential is advantageous in systems operating with fast output pulses and high counting rates. The only drawback is that the photocathode end of the tube must be well-insulated from ground to prevent corona discarge near the photocathode.

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.

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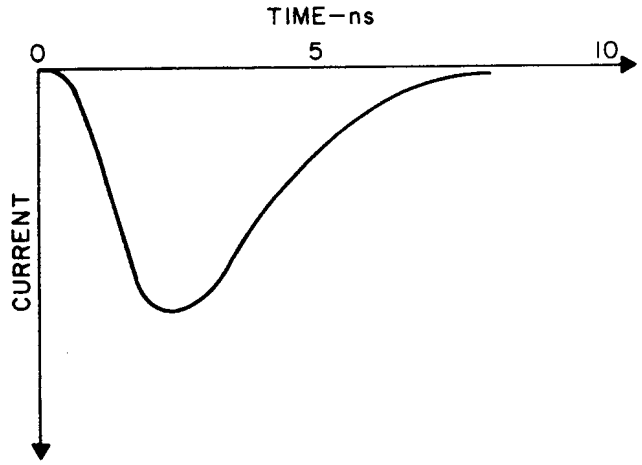
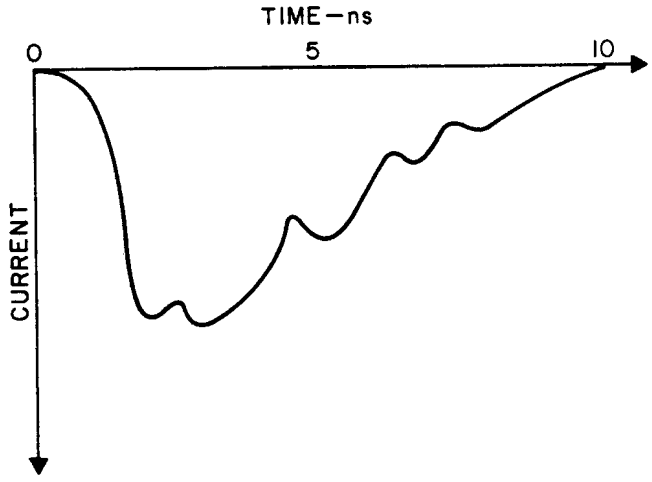
Connections to the anode and adjacent dynodes must be made with low inductance to avoid parasitic resonances.

Upper waveform: correct pulse
Lower waveform: superimposed “ringing” due to parasitic resonances





(from *Burle Photomultiplier Handbook*)

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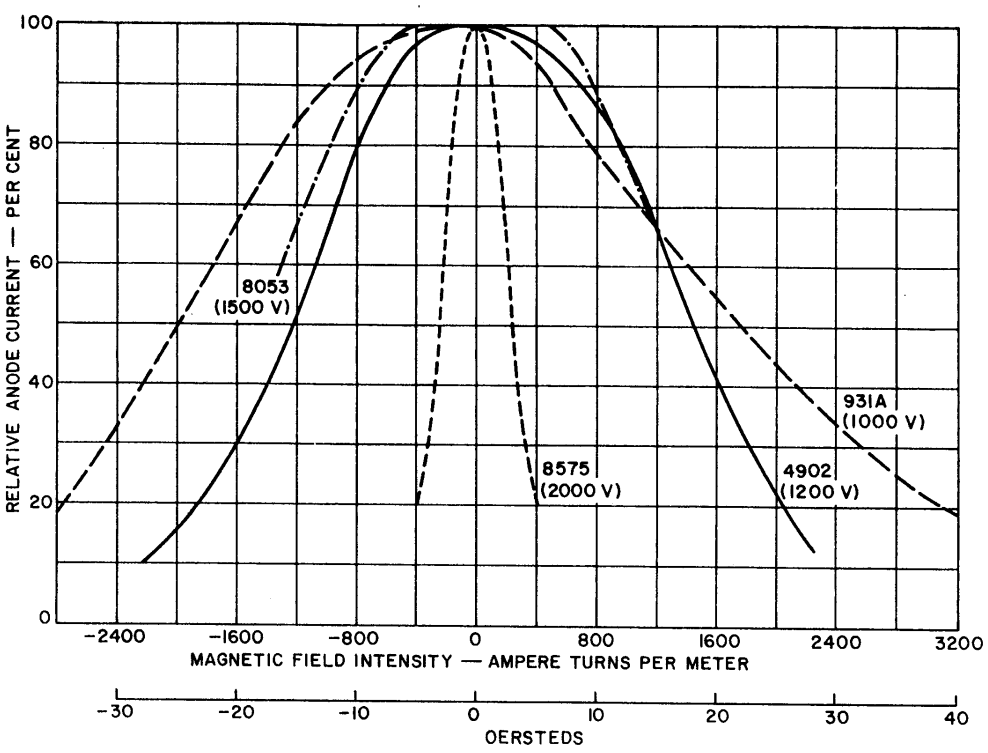
Photomultiplier tubes are sensitive to magnetic fields



(from *Burle Photomultiplier Handbook*)

Even in a laboratory environment, PMTs must be surrounded by magnetic shielding ("mu metal") to avoid orientation-dependent gain changes due to stray magnetic fields.

Typical: 25% decrease in gain at 0.1 mT

Conventional PMTs will not function inside the magnet of a tracking detector!

Alternatives: MCP PMTs
Semiconductor photodiodes
special dynode structures

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Time Response of Photomultiplier Tubes

For a typical fast 2” PMT (Philips XP2020) the transit time from the photocathode to the anode is about 30 ns at 2000V.

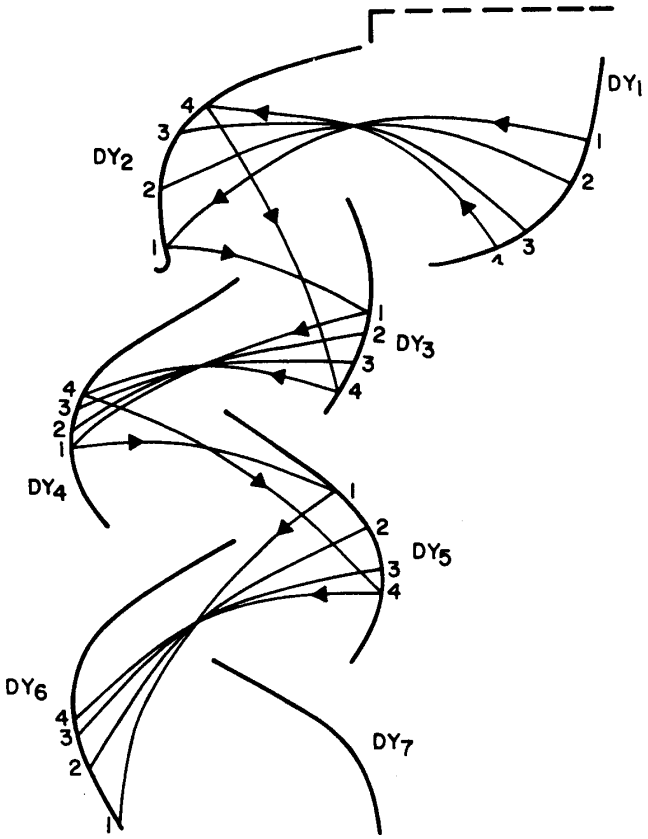
The intrinsic rise time is 1.6 ns, due to broadening of the initial electron packet in the course of the multiplication process.

The transit time varies by 0.25 ns between the center of the photocathode and a radius of 18 mm.

For two tubes operating in coincidence at a signal level of 1500 photoelectrons, a time resolution of 230 ps is possible.

Special dynode structures are used to reduce transit time spread.

Example: time compensating structure



(from *Burle Photomultiplier Handbook*)

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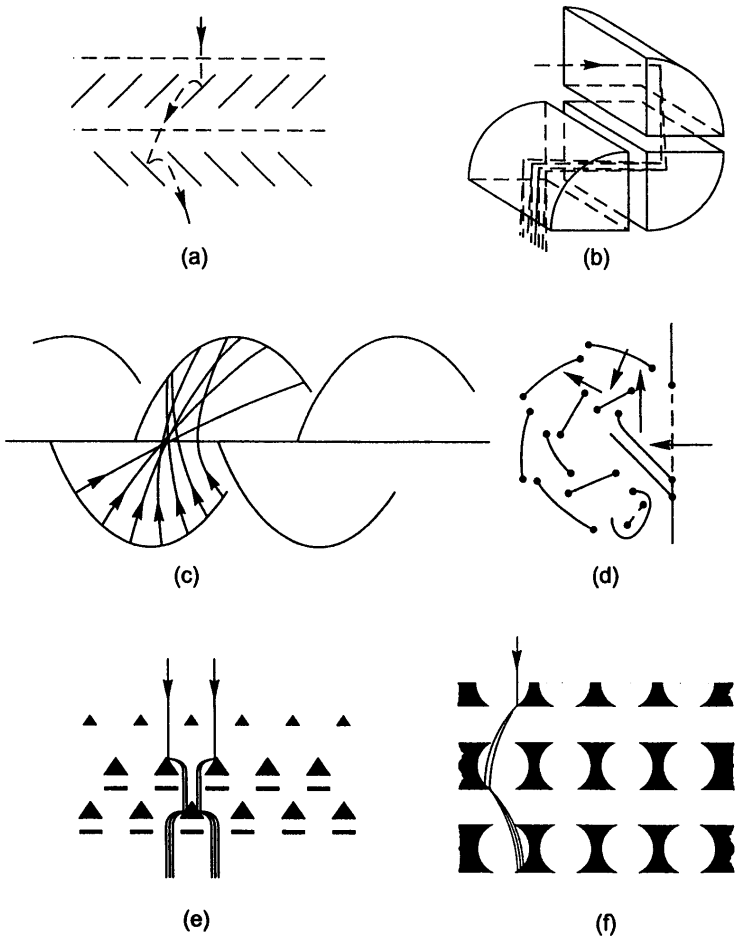
Various Dynode Structures



(from *"Photomultiplier Tubes"*, Philips Photonics)

a) Venetian blind
   Allows simple input system with high collection efficiency.
   Good gain stability, but mediocre timing performance
b) Box and Grid: characteristics similar to a)
c) Linear focusing: good timing characteristics
d) Circular cage: compact
e) Mesh dynodes: low gain, but usable up to B= 1 T
f) Foil dynodes: perforated metal foils – particularly useful for multi-channel anodes