Week 6: Ch. 8 Scintillation Counters

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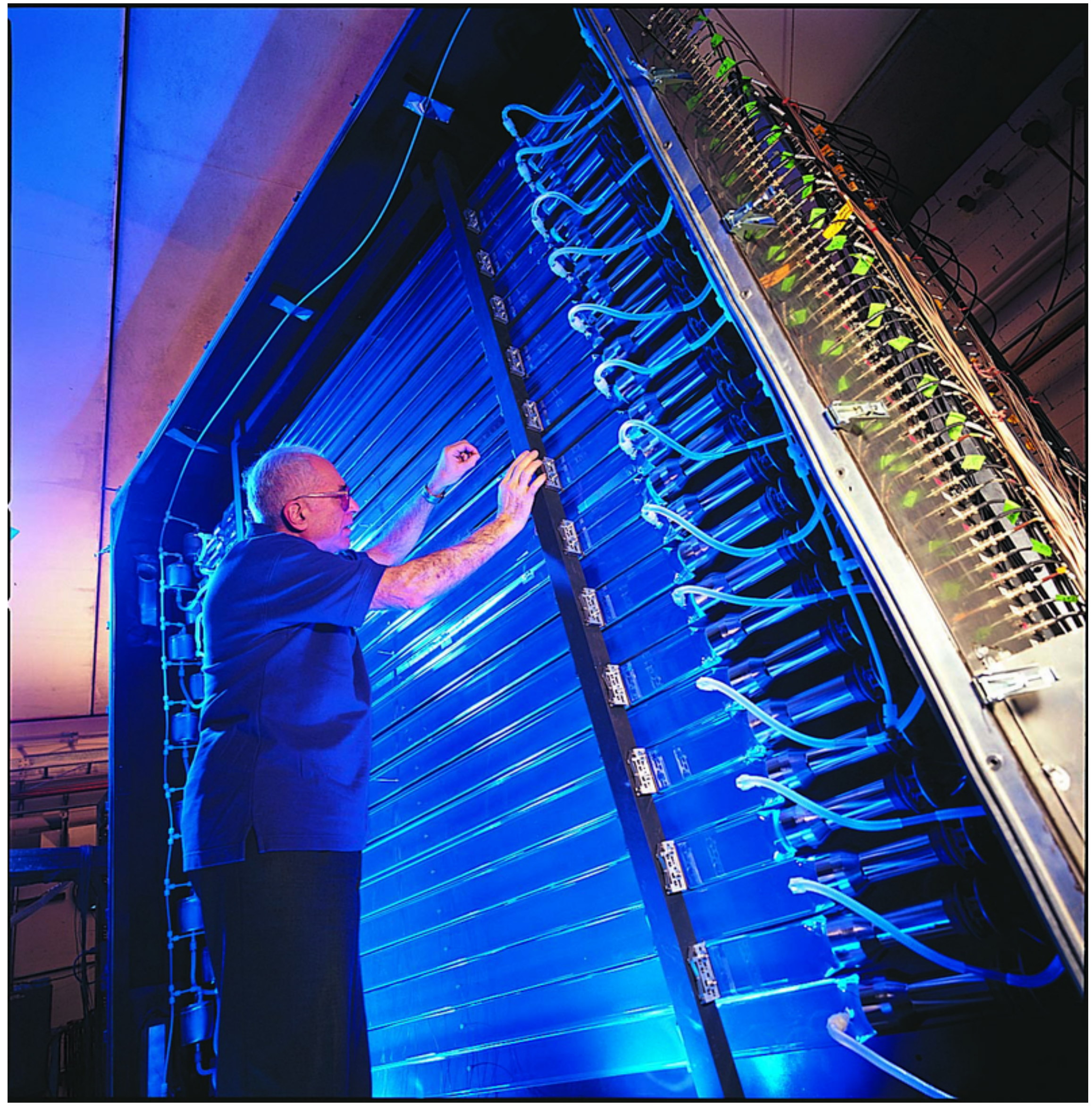
Proportional Counters

Principles of Scintillation Counters

-- organic materials
--- light production
-- inorganic materials
--- light production
-- light output, collection
-- position measurement



Photomultiplier Devices

Chapter 9: Scintillation Counters

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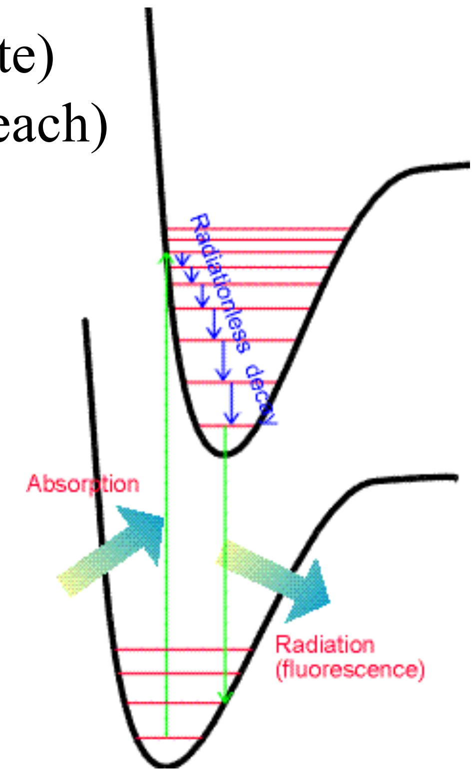
We have seen that photons are produced in de-excitation of primary ionization, *scintillation devices* rely on enhancing and detecting these photons. The primary ionization is ignored and these materials are generally insulators for reasons that we will discuss in a moment.

General requirements:

- •Linear conversion of ΔE into photons (some only approximate)
- •Efficient conversion into (near) visible light (few eV or less each) (e.g., NaI(Tl): 38k/MeV a value similar to N_{IP})
- •Transparent to scintillation photons, good optical medium
- •Short decay time for fluorescence (ns OK, ps good)
- •Good mechanical properties (n~1.5 for silicate glass)

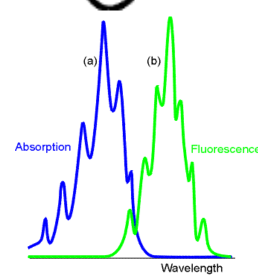


Scintillator classes:

Organic molecules – molecular transitions in fluor

Inorganic materials – generally transitions in atomic dopants

Molecular energy cycle for photon absorption/emission: Notice that there is always a 'red-shift' in the emitted photons – energy loss, inefficiency – but good for transmission.



Scintillation Counters – Organic Materials

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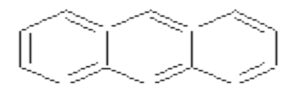
Anthracene is (for historical reasons) the standard organic scintillator, it can be crystallized in pure form and packaged for use as a detector. ~ 20k hν / MeV

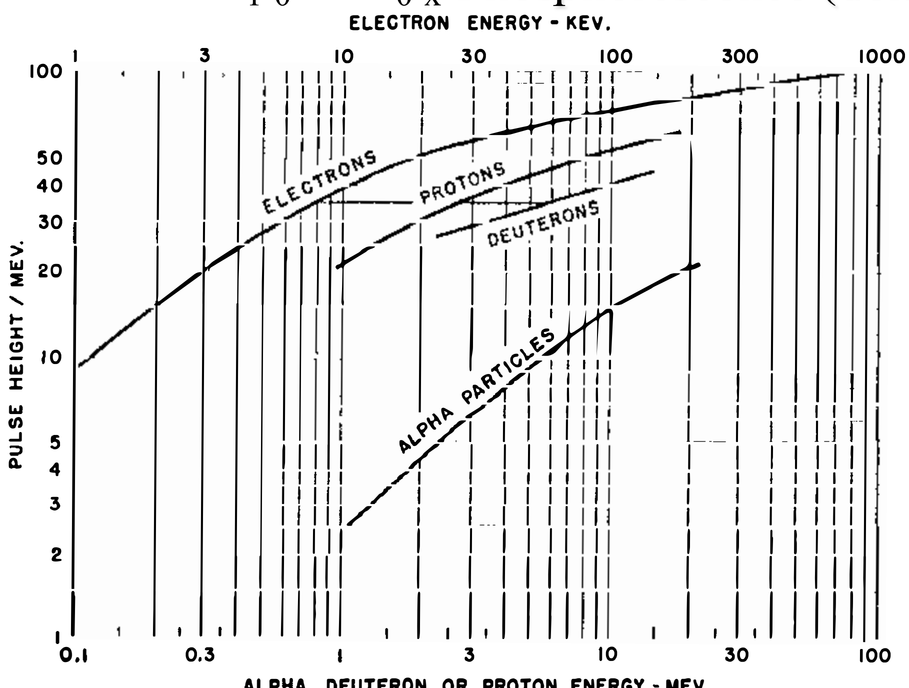


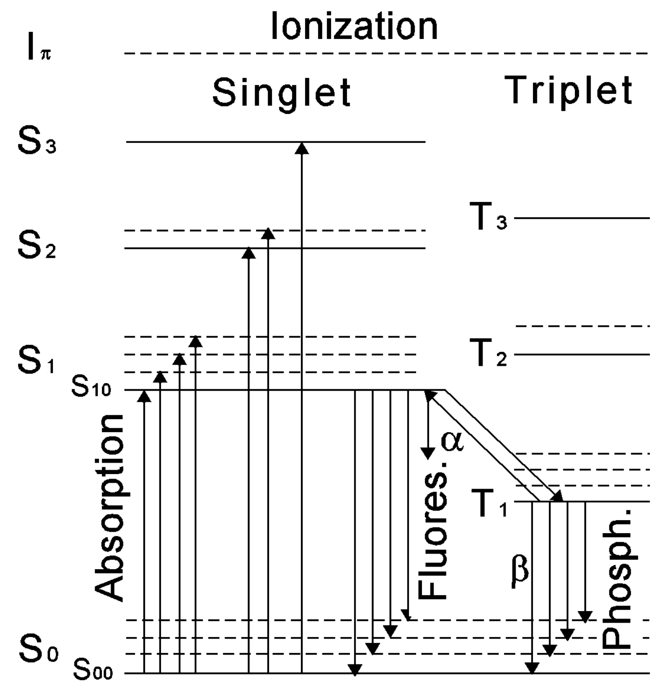
- Ground state: *singlet* (all electrons are paired)
- Dipole photon excitation shown to *singlet states*
- Rapid vibrational transitions to $S_{1\text{-}0}$ state followed by dipole transition to ground electronic states

$$S_{1\text{-}0} \rightarrow S_{0\text{-}x} \quad \text{Fluorescence (fast)}$$

- Occasional intersystem crossing Singlet→Triplet
- Slow spin-flip transition to ground electronic states

$$T_{1\text{-}0} \rightarrow S_{0\text{-}x} \quad \text{Phosphorescence (delayed)}$$





The amount of light and the fraction that ends up in the slower transitions depends on the molecule and on the excitation mechanism. N.B. very nonlinear

From *R. Swank, Annl. Rev. Nucl. Sci. 4 (1954) 111*

Scintillation Counters – Light output, time

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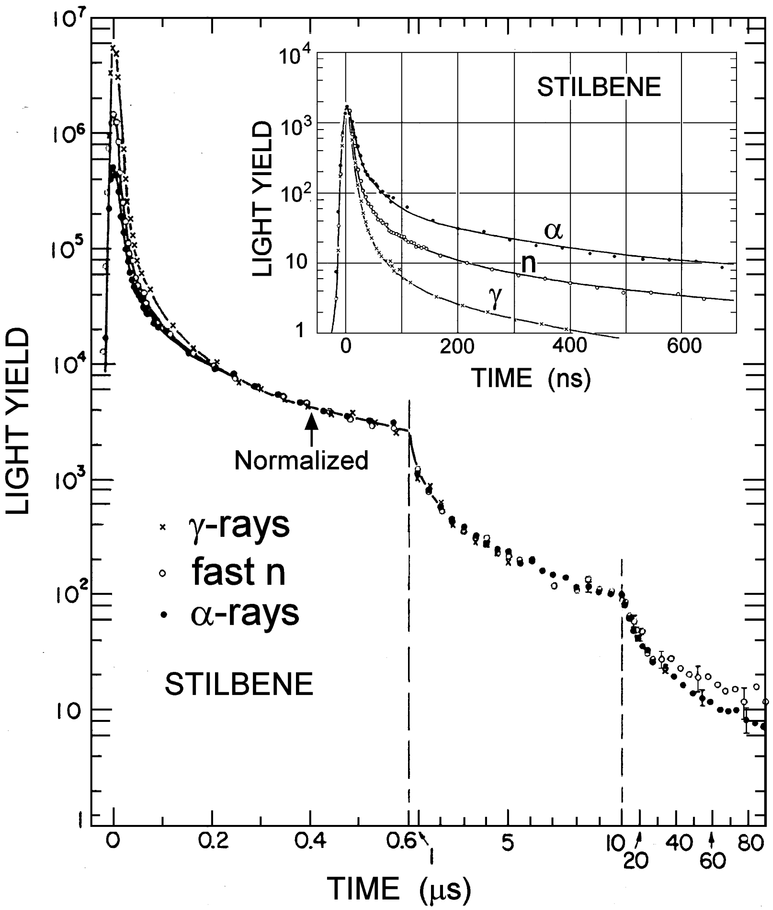
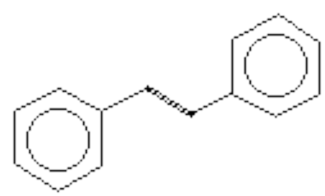
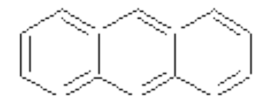
Time distribution usually has two components … fast one (dipole, $\tau \sim \lambda^2$) and then an exponential decay, additional exponential components are possible if there are other nearby triplet states. Changes in the feeding of the triplet state will change the decay shape …

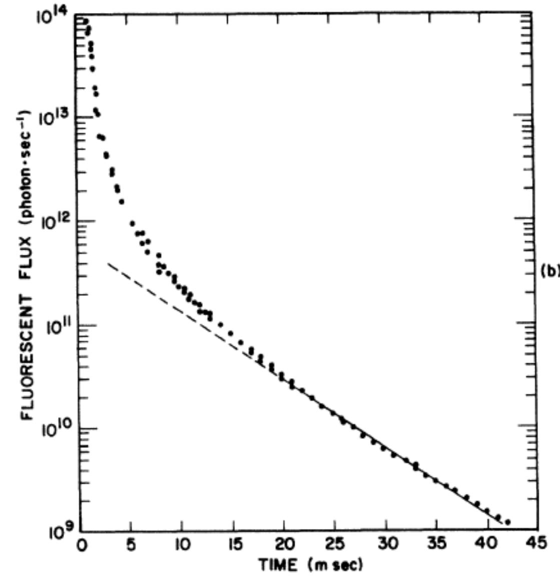


Inset: Fig. 8.5 Knoll, 3rd Ed.



anthracene



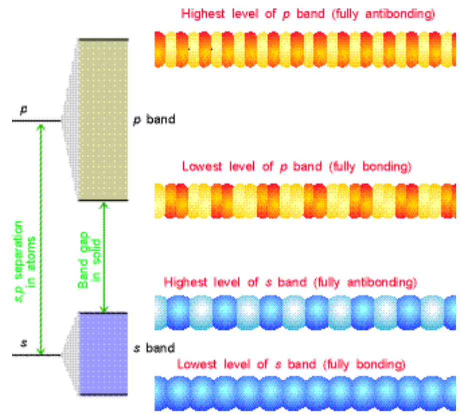


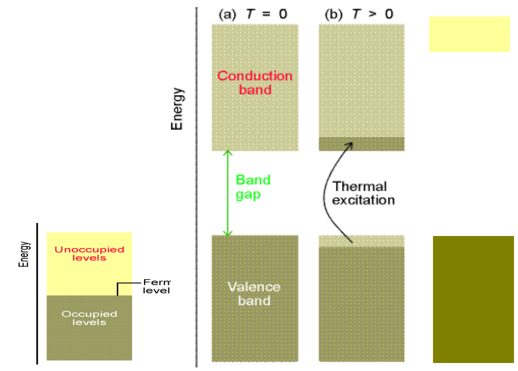
From *R.G. Kepler, et al. Phys.Rev.Lett.10 (1963) 400*

Organic scintillators rely on adding specific molecules to a "solution" to emit the photons. These molecules will be damaged by the primary radiation and lead to a finite lifetime for the detector. Damage at doses:
$\sim 10^3 - 10^4$ Gray $\rightarrow 10^{+12} - 10^{+14}$ MeV/g

Scintillation Counters – Inorganic Materials – 1

The band theory of solid materials in one sentence: the regular structure of the lattice and close proximity of atoms allows electron "molecular" orbitals that extend over the entire lattice whose energies merge into bands that preserve the underlying atomic orbital energy pattern.





Metal Semiconductor Insulator

The primary radiation creates an electron/hole pair which can recombine in various ways depending on the material and dopants or activators. The energy necessary to create a surviving pair is about 1.5-2 times the gap in ionic crystals and twice this in covalent (i.e., organic) materials.

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

•Interleaved band structure of anions/cations in lattice, BaF_2

•Electron (or hole) is trapped by impurity with levels in band-gap, NaI(Tl)

All of these processes emit photons with energies less than the size of the band gap. The dopant is (usually) chosen to provide visible photons.

Scintillation Counters – Inorganic Materials – 2

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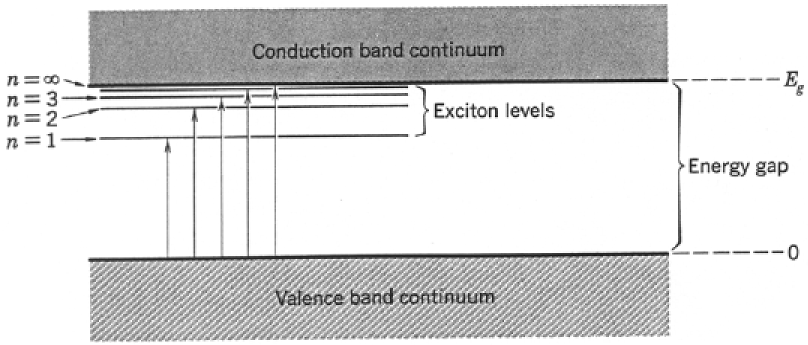
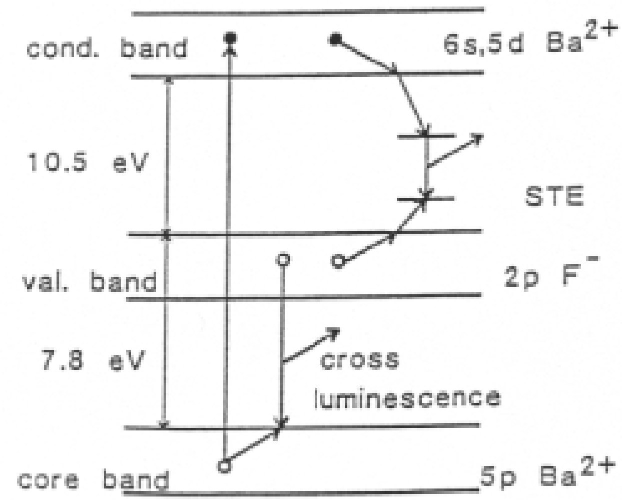
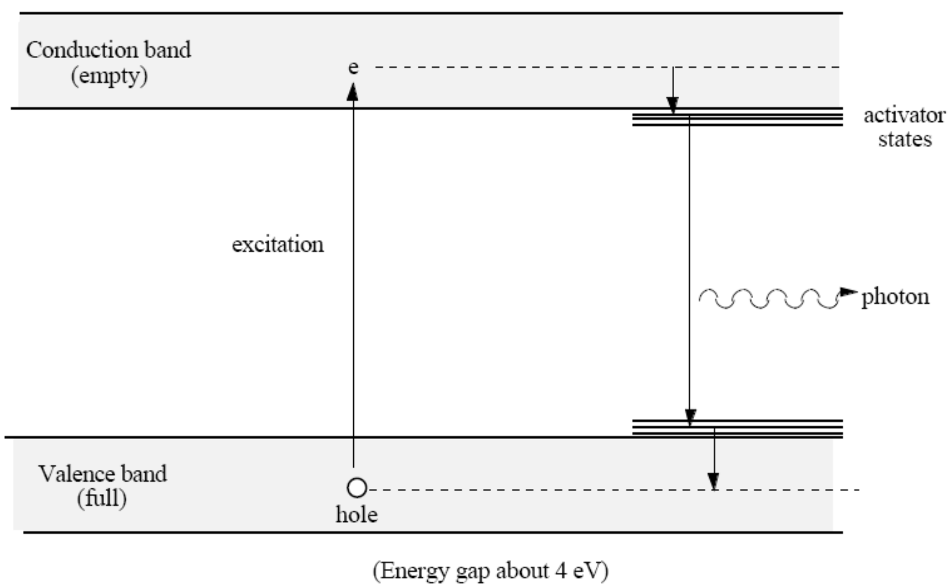


The exciton system, bound e-/hole



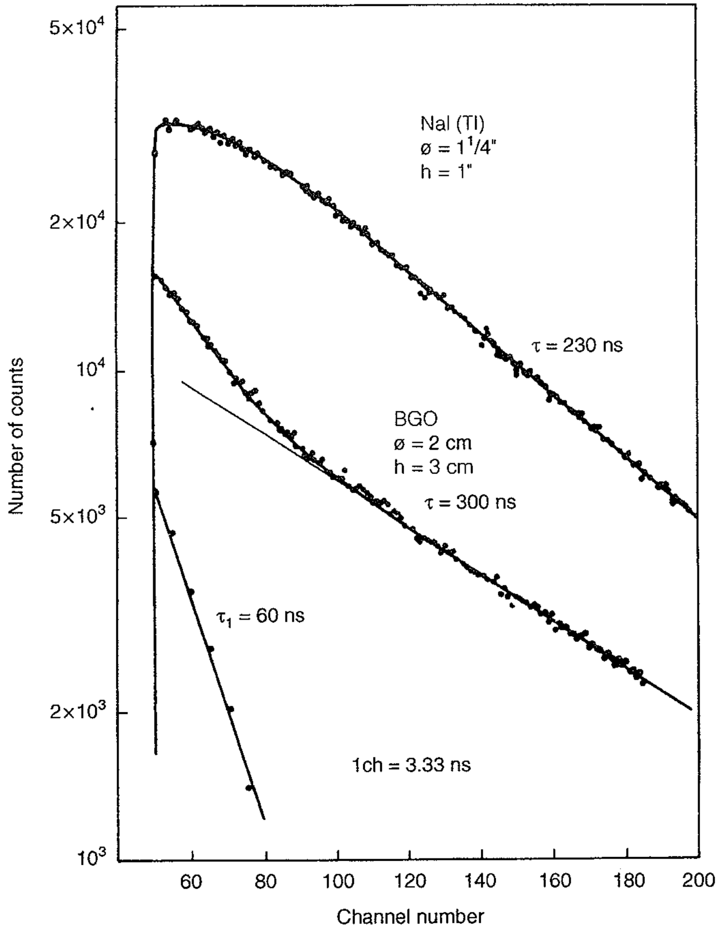
Core-valence transition, & conduction-valence trans.



NaI – transition by *Tl* dopant

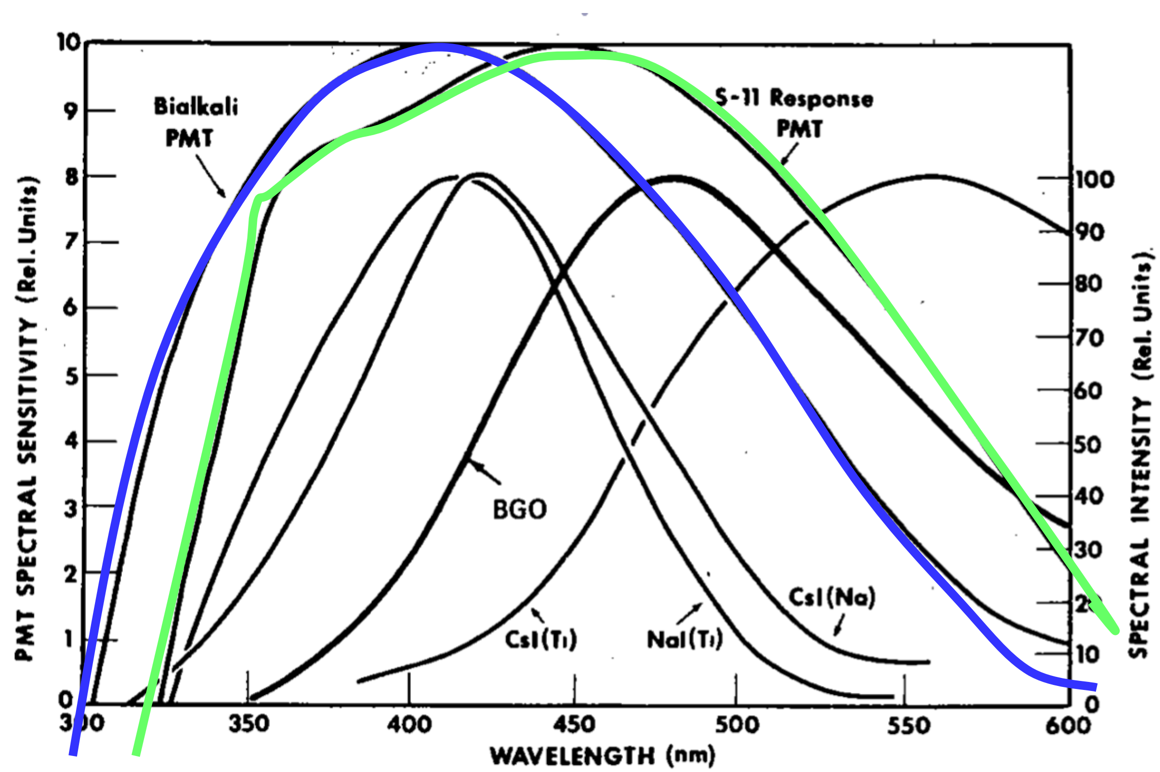
Note that the amount of excitation energy will be random, the energy above the bottom of the conduction band is lost (thermalized) as well as that below the top of the valence band. This loss is not important if the remaining energy is efficiently transferred to the dopant and if the dopant has a high quantum efficiency.

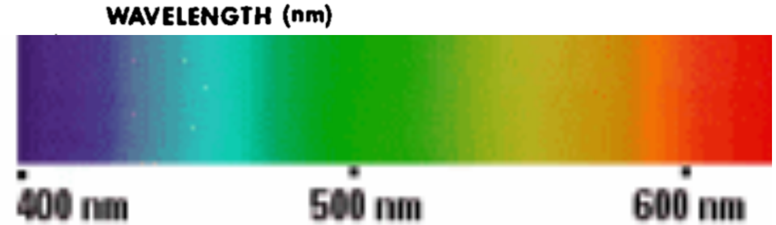
Scintillation Counters – Light output: color



The time spectra of the materials varies dramatically – this will affect the ultimate time resolution of a given detector.

Fig. 8.11 Knoll, 3rd,4th Eds.





The emission spectrum of the material should match the spectral response of the photon detector for maximal efficiency … (obvious)

Fig. 8.7 Knoll, 3rd,4th Eds.

Scintillation Counters – Light output: Temp.

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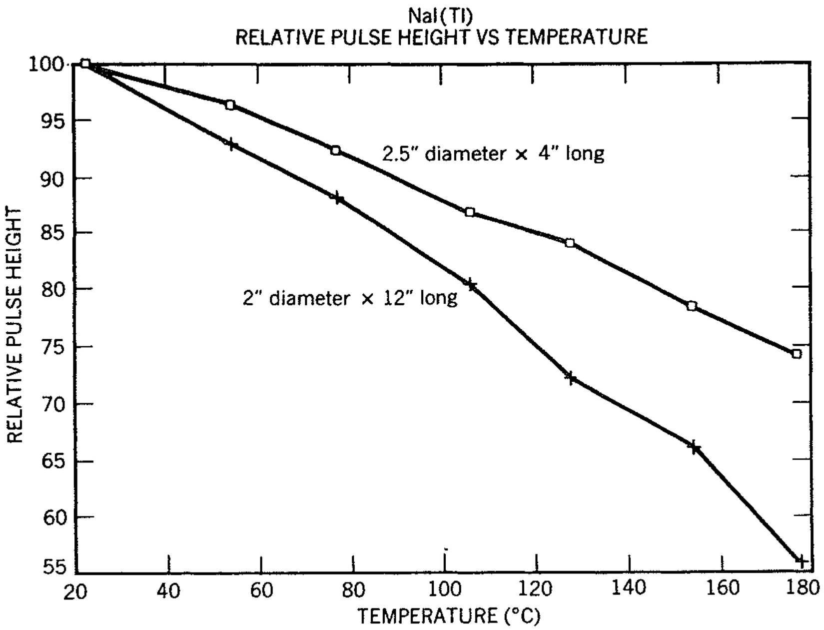


Fig. 8.9 Knoll, 3rd,4th Eds.

Cooling the material generally leads to higher light output, less loss through other processes (trapping, etc.). Thus, cooling can also change the relative amounts of components.

Note figure 8.12 is relative to BaF_2, not absolute scale. BGO is especially temperature sensitive (also lowest light output).

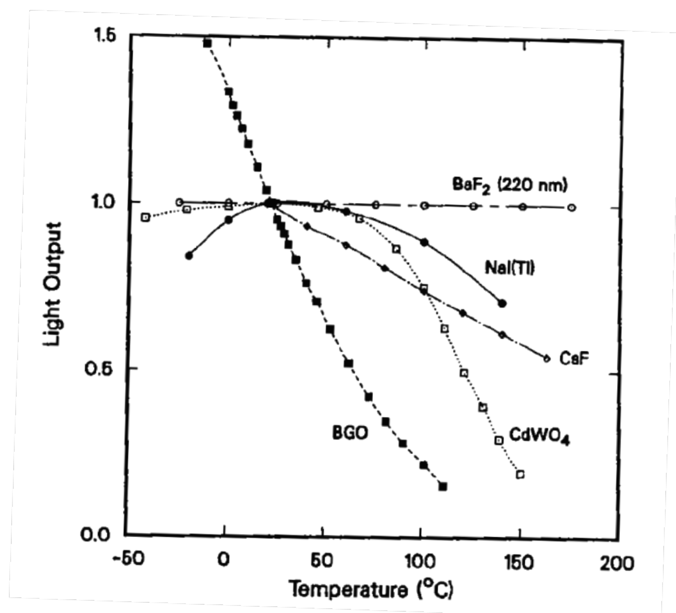


Fig. 8.12 Knoll, 3rd,4th Eds.

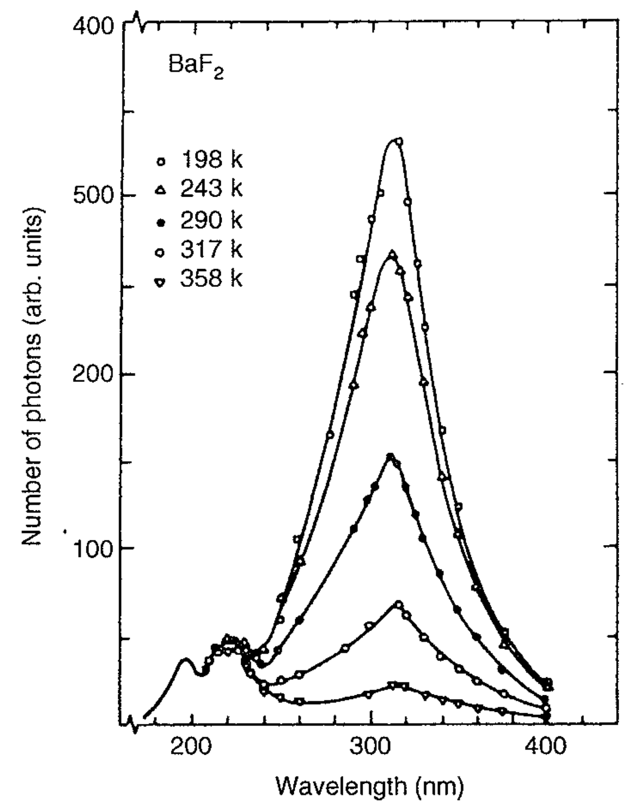
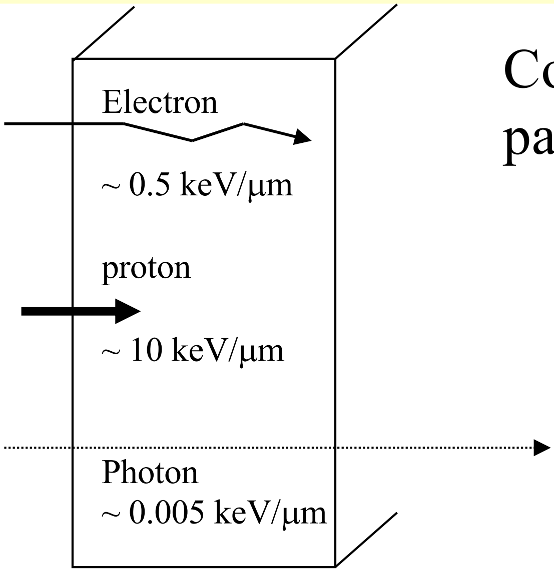


Fig. 8.13 Knoll, 3rd,4th Eds.

Scintillation Counters – Light output/Track



Consider the light output as a function of track length for three particles with 1 MeV incident on a (organic) scintillator:

$$\frac{dL}{dx} = S\frac{dE}{dx} \quad \textit{no recombination, etc.}$$

where S is the sensitivity of the material (next). In reality:

$$\frac{dL}{dx} = S\frac{dE}{dx} \Bigg/ \left(1 + kB\frac{dE}{dx}\right)$$

$$\frac{dL}{dx} = S\frac{dE}{dx} \quad \textit{when} \quad \frac{dE}{dx}\ \textit{is small}$$

$$\frac{dL}{dx}\left(\frac{dE}{dx}\right)^{-1} = S \quad \textit{or} \quad \frac{dL}{dE} = S$$

$$\int dL = \int S\,dE \quad \rightarrow \quad L = S * E$$

$$\frac{dL}{dx} = \frac{S}{kB} \quad \textit{when} \quad \frac{dE}{dx}\ \textit{is large}$$

$$\int dL = \int \frac{S}{kB}dx \quad \rightarrow \quad L = \frac{S}{kB}x$$

N.B. “k” (quenching) and “B” (recombination) are multiplied together and thus there is effectively one constant.

Scintillation Counters – Light Transmission

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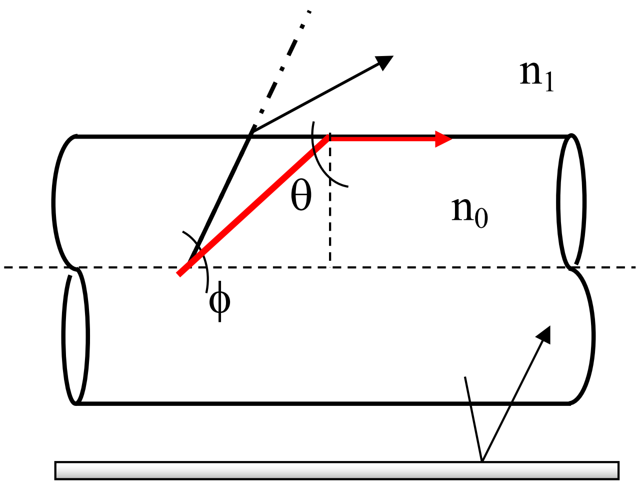
Scintillation efficiency or "Sensitivity": the energy in the emitted photons compared to the energy of the incident radiation. $S = N_{h\nu} * (hc/\lambda) / E_{incident}$

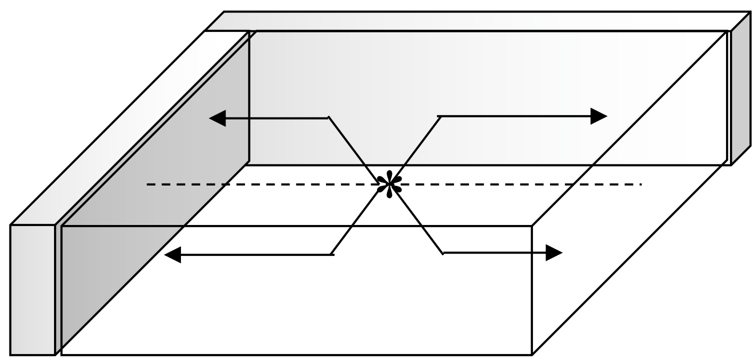
Round solid tube – light guide or scintillator – light pipe



Reflector – specular or *diffuse*

Internal reflection of light up to some critical angle, θ_c where $\sin\theta_c = n_1/n_0$ note that θ_c is normal to surface.

$$f = \frac{\Omega}{4\pi} = \frac{1}{4\pi}\int_0^{\varphi_C} 2\pi \sin\varphi \, d\varphi \rightarrow f = \frac{1}{2}(1-\cos\varphi_C) = \frac{1}{2}\left(1-\frac{n_1}{n_0}\right)$$



Slab: All edges

$$f = \frac{1}{2}\sqrt{1-\left(\frac{n_1}{n_0}\right)^2}$$

Attenuation Length: the light will suffer a Beer's Law attenuation along the path $I = I_0 e^{-x/L}$ where "L" is a characteristic attenuation length. L=2 m for a "good" material.

Scintillation Counters – Sandwiches

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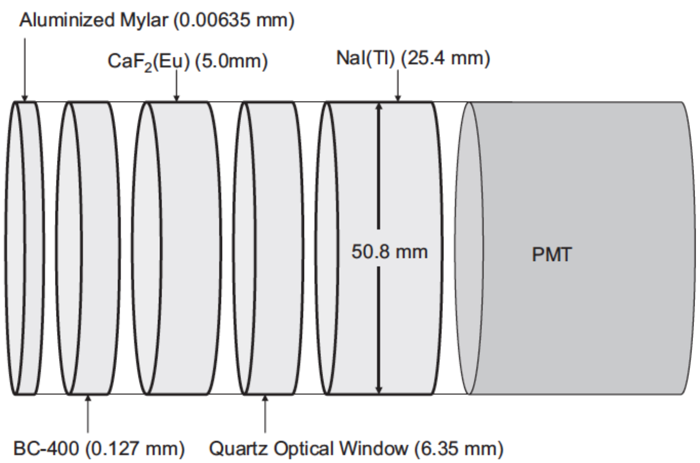
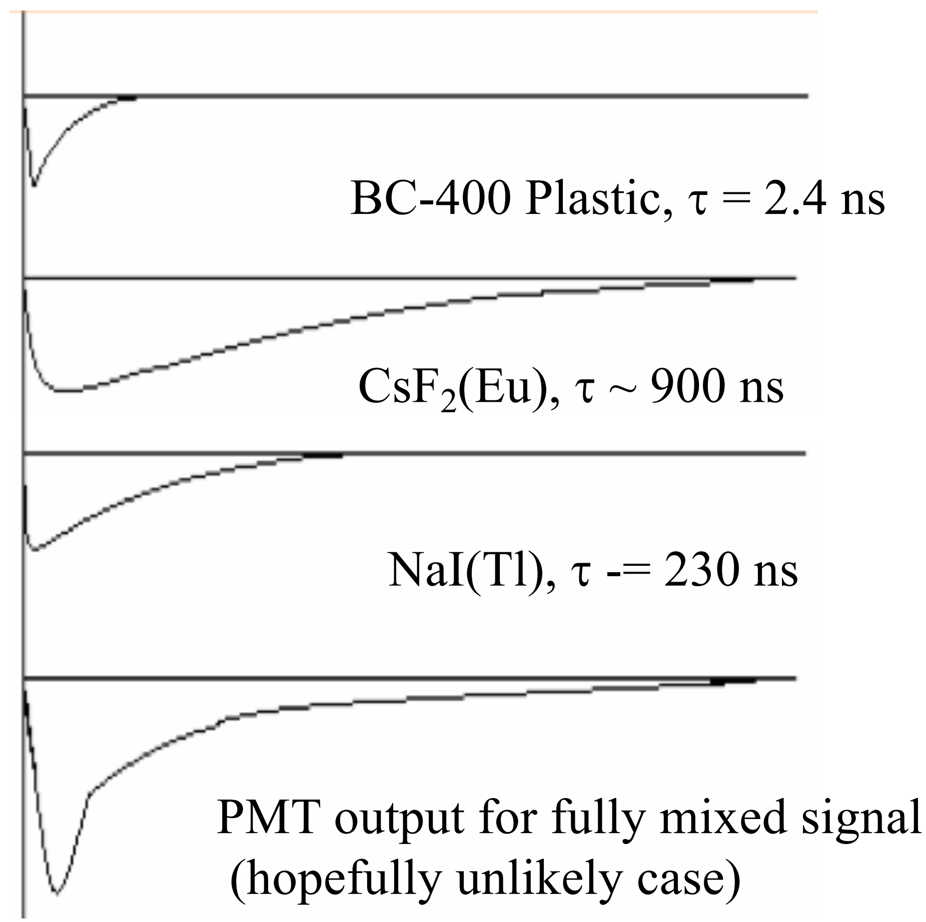
Note that Scintillation Crystals are generally transparent to visible light and could act as a "light guide" for another scintillator… Note that different scintillation materials generally have different decay constants and may have different sensitivities to radiations. Time-gated signal processing could be used to disentangle the multiple pulses.

A triple scintillator for Radiation Survey: Farsoni &Hamby NIM A578 (2007) 528





Scintillation Counters – "Phoswich" Example

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Note that Scintillation Crystals are generally transparent to visible light and could act as a "light guide" for another scintillator… Note that different scintillation materials generally have different decay constants and may have different sensitivities to radiations. Time-gated signal processing is necessary to disentangle the multiple pulses.

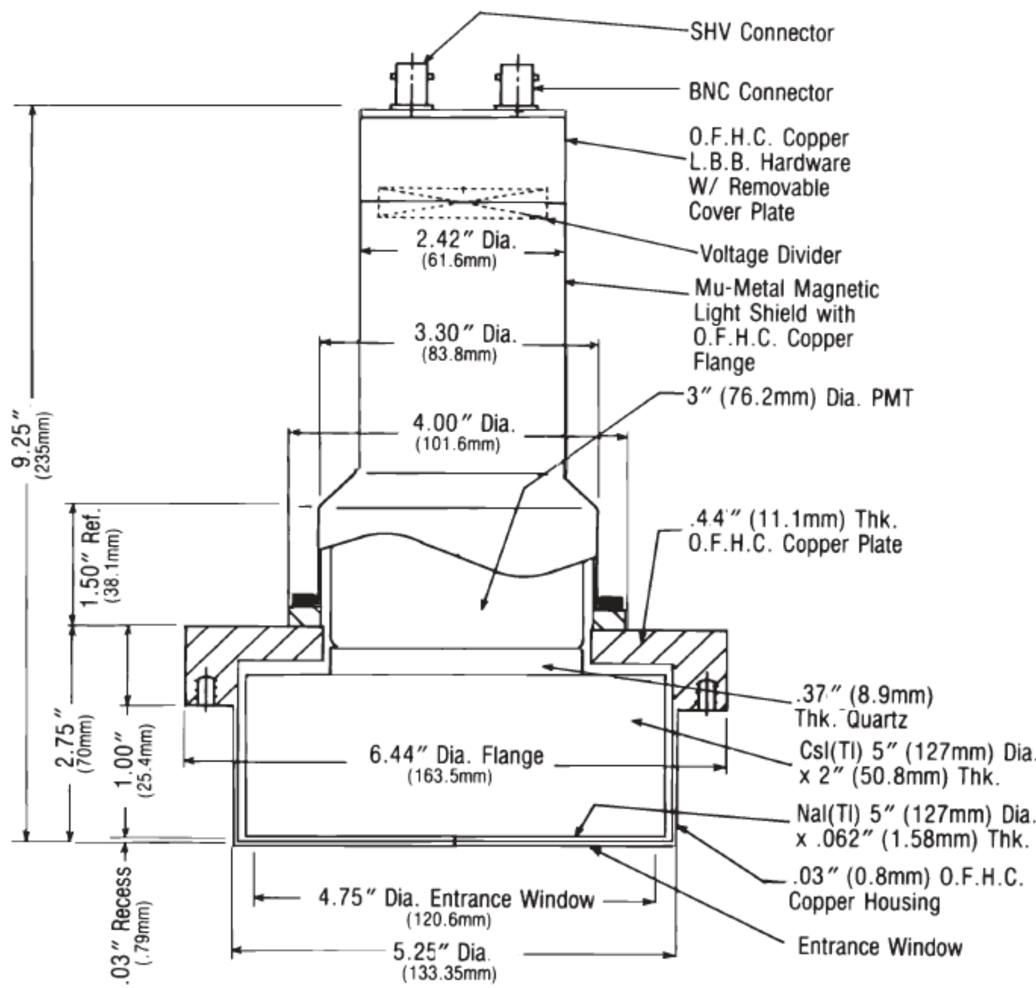
A commercial double crystal for "whole body" counting to suppress cosmic rays and external gammas made by St. Gobain

http://www.crystals.saint-gobain.com

CsI(Tl) , $\tau \sim 1\ \mu s$

NaI(Tl), $\tau = 230$ ns

This technique is occasionally used in nuclear science, somewhat tricky to unravel.



Scintillation Counters – Comparison

	Inorganic	Organic
Mechanism	Excitons recombine at dopants/color centers	Deexcitation of molecular π-electrons
Efficiency of conversion into photons	Wide range: 0.1 NaI(Tl), 0.001 $PbWO_4$	Narrow range: 0.02 – 0.04
Track quenching	Small	Large
Time constant	Slow (~ μs)	Fast (tens of ns)
Temperature dependence	Large	Small
Radiation Damage	Creation of long term trapping centers	Destruction of primary fluors
Density	Generally high, 3.67 NaI(Tl), 8.28 $PbWO_4$	Always low, 1 g/cm^3 ~ CH_2
γ-ray detection/spectroscopy	Important	Nearly insensitive
Pulse-shape discrimination	Possible in some cases	Fast/slow for γ/n

Example Question

Knoll: 8.9, (paraphrased)

(a) Can a person see the flash of light created when a 1 MeV beta particle is absorbed in a NaI(Tl) crystal? Assume that the person's eye has a iris diameter of 3 mm that is 10 cm away from the crystal.

(b) Can this person see the flash of light when a 6 MeV alpha particle strikes a CdS scintillator under the same conditions? [Hans Geiger's job in grad school.]