
Scintillation and Light Sensitive Detectors - I

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How Particles Produce Light

- charged particles can produce light in materials
 - Čerenkov radiation
 - scintillation in some materials due to excitation and ionization
 - transition radiation
 - neutral particles (e.g. γ and n) must interact first and the resulting electrons, protons, recoiling nuclei or other charged hadrons produce light
-

Electromagnetic Interaction Between a Charged Particle and an Atom

- charged particle
 - mass m , energy γm , momentum $\gamma m \mathbf{v}$
 - moving along z -axis $\mathbf{v} = (0,0,v)$
 - exchanges a real or virtual photon with atom
 - atom at $(0,y,z)$
 - photon energy $\hbar\omega$, momentum $\hbar\mathbf{k}$
 - four momentum is conserved in the interaction
 - $p = p' + p_\gamma$
 - easy to show that for photon energies ($\hbar\omega \ll \gamma m$)
 - $\omega = \mathbf{v} \cdot \mathbf{k} = v k_z$
-

Electromagnetic Interaction Between a Charged Particle and an Atom cont'd

- dispersion relation in material:

$$\omega^2 = \frac{k^2 c^2}{\varepsilon} \quad \varepsilon = \varepsilon_1 + i\varepsilon_2 \quad \varepsilon_1 = n^2$$

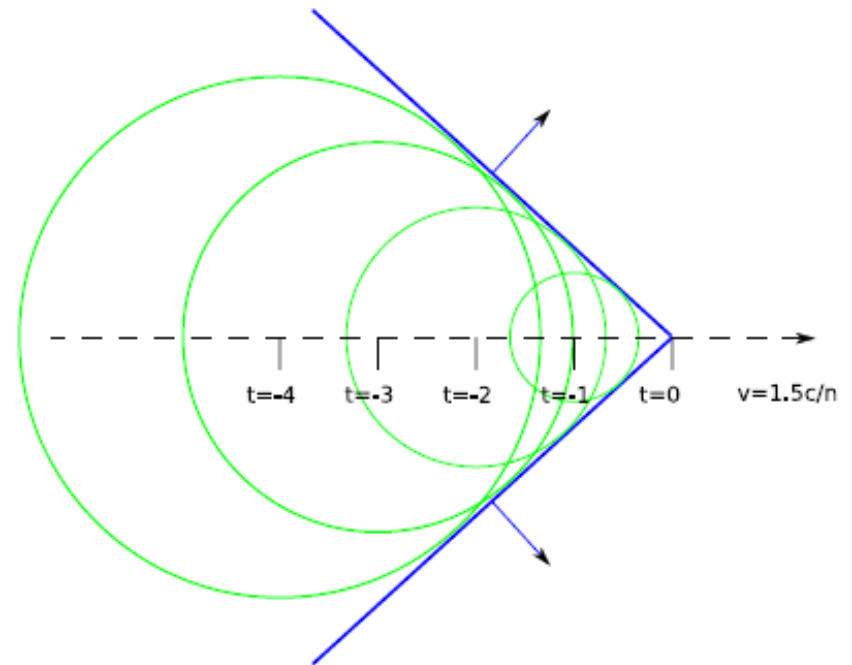
$$k_y^2 + k_z^2 = \omega^2 \varepsilon / c^2$$

- photon of the interaction has $k_y = \frac{\omega}{v} \sqrt{\frac{v^2 \varepsilon}{c^2} - 1}$
- for photon energies that don't excite the material, the dielectric constant ε is real and $\varepsilon = n^2$
- then, for $v > c/n$, k_y and k_z are real and a real photon can propagate due to the interaction

Čerenkov Light

- emitted by charged particles whose velocity exceeds c/n
- results in a coherent shock wavefront that's a cone of light
- half angle given by:
 - $\cos \theta = 1 / [\beta n(\lambda)]$
 - $\beta = v/c$
 - e.g. 41° in water for $\beta \approx 1$
- spectrum of photons emitted:

$$\frac{dN}{dx d\omega} = \frac{\alpha}{c} \left(1 - \frac{1}{n^2(\omega)\beta^2} \right)$$



from <http://www.magic.mppmu.mpg.de/publications/theses/JLopez.pdf>

Characteristics of Čerenkov Light

- it's prompt
 - basically flat frequency spectrum of the emitted light
 - that's what distinguished it from fluorescence which exhibits bands in the emitted spectrum
 - which means it goes as $\frac{dN}{d\lambda} \propto \frac{1}{\lambda^2}$
 - hence it's UV and blue light
 - cannot be harder UV because most materials start to absorb at shorter wavelengths and ϵ must be real
-

Transition Radiation

- produced at the boundary between materials that have different dielectric properties
 - can be considered as the constructive interference of Čerenkov radiation from the two different materials across the discontinuity
 - works even below the Čerenkov threshold
 - works even for $\varepsilon_1 < 1$, especially for X-ray frequencies
 - in those cases which would otherwise have no real Čerenkov photon propagation in a uniform medium, the interference of the EM fields across the discontinuity, in the finite length radiator, produces real photons
 - from Wikipedia: the electric field of the particle is different in each medium, [and] the particle has to “shake off” the difference when it crosses the boundary
 - I’ll not discuss further...I’ve not worked with transition radiation detectors before
-

Scintillation

- the physics definition of scintillation:
 - the process by which ionization produced by charged particles excites a material and light is emitted by the de-excitation
 - one of the most common detection techniques in nuclear and particle physics
 - earliest use by Crookes in 1903
 - a ZnS-coated screen scintillates when struck by α particles
 - then Curran and Baker in 1944
 - coated a photomultiplier tube with ZnS producing the first scintillation counter that didn't require the human eye
 - since then many forms of scintillation detectors, large and small, have been developed
 - the scintillation process differs in different materials (e.g. inorganic crystals, organic liquids, noble gases and liquids, plastic scintillators)
 - we'll briefly examine each type...
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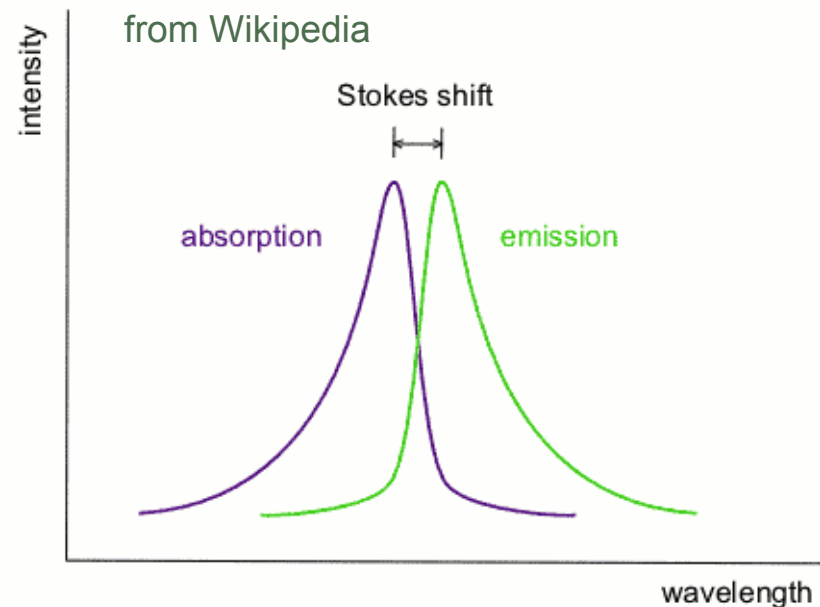
Aside: Definitions

- when you excite a material (not thermally) and it subsequently gives off light, that is *luminescence*
 - how it's excited determines the type of luminescence (e.g. *photoluminescence*, *chemiluminescence*, *triboluminescence*)
 - *fluorescence* is photoluminescence or scintillation (i.e. excitation produced by ionizing radiation) that has a fast decay time (ns to μ s)
 - *phosphorescence* is the same, only with a much slower decay time (ms to seconds)
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Stokes Shift

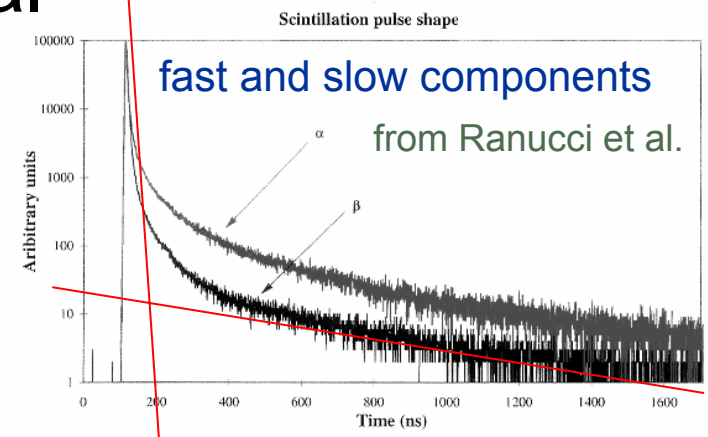
an important, general concept to keep in mind for all scintillators

- emitted photons are at longer wavelengths (smaller energies) than the energy gap of the excitation
- the processes that produce this “Stokes shift” are different in different scintillating materials
- this allows the scintillation light to propagate through the material
 - emitted photons can't be self-absorbed by exciting the material again



Scintillator Characteristics of Interest

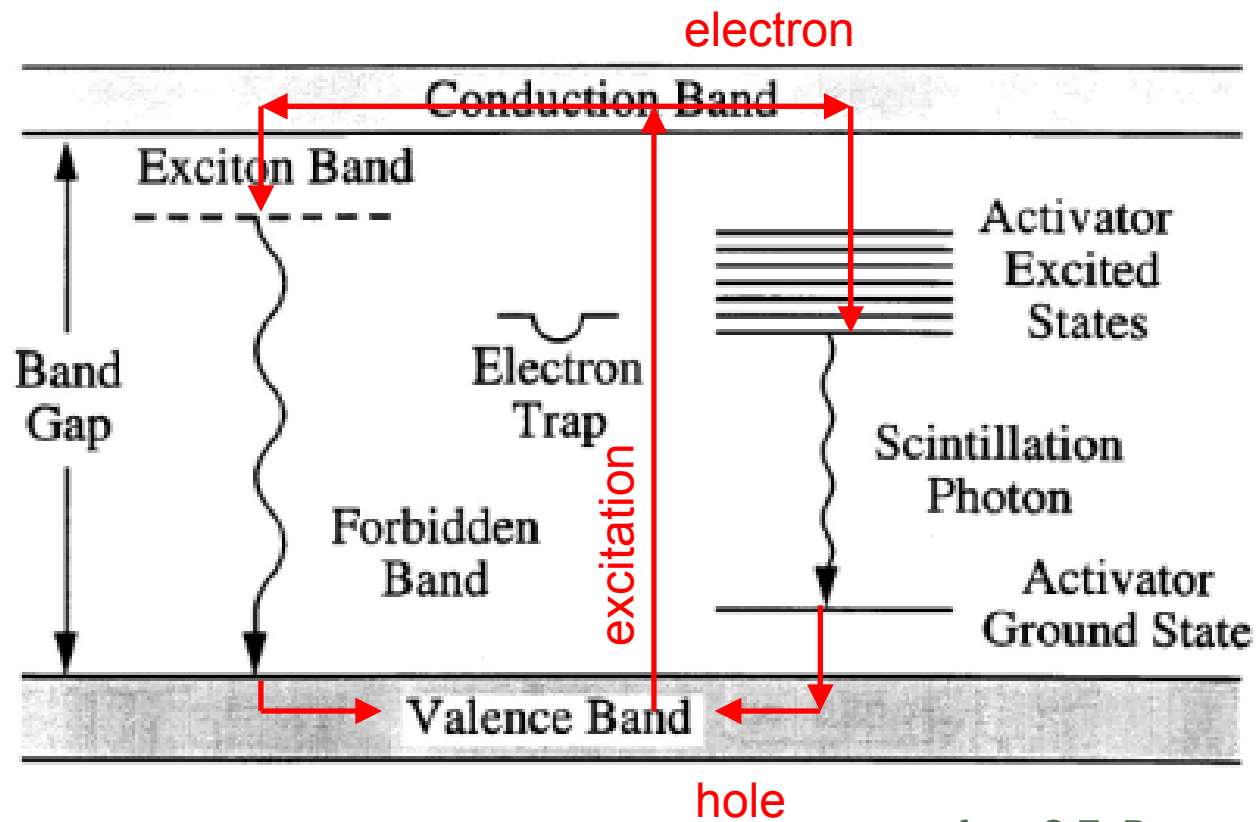
- **light yield:** high efficiency for converting ionization energy to light output [photons/MeV]
- **emission spectrum:** overlaps with spectral response of light detector (e.g. PMT)
- **decay time:** can have several time constants
- **density and Z:** determine response to γ , e^- and other electromagnetic processes



Inorganic Crystals

- the scintillation mechanism requires the crystal band structure
 - you can't dissolve NaI in water or melt these crystals and get scintillation
 - most are impurity activated
 - luminescence centres are associated with the activator sites in the lattice
 - interstitial, substitutional, excess atoms, defects
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Inorganic Crystal Band Structure



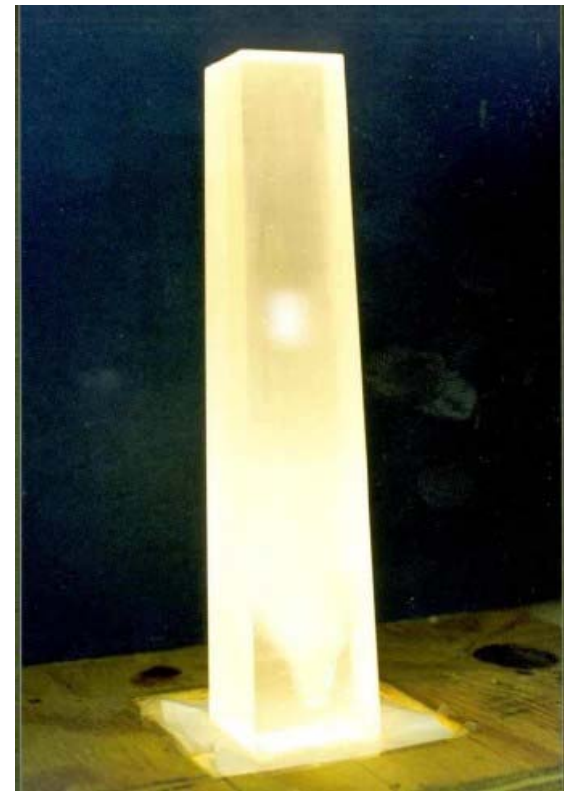
from S.E. Derenzo

Doped Inorganic Crystals

- decay time primarily depends on the lifetime of the activator excited state
- examples of doped crystals
 - NaI(Tl)
 - CsI(Tl)
 - $\text{CaF}_2(\text{Eu})$
 - $\text{LaBr}_3(\text{Ce})$



typical NaI(Tl) detector
in Queen's undergraduate lab



CsI(Tl) from BaBar
Roma group

Exciton Luminescence in Crystals

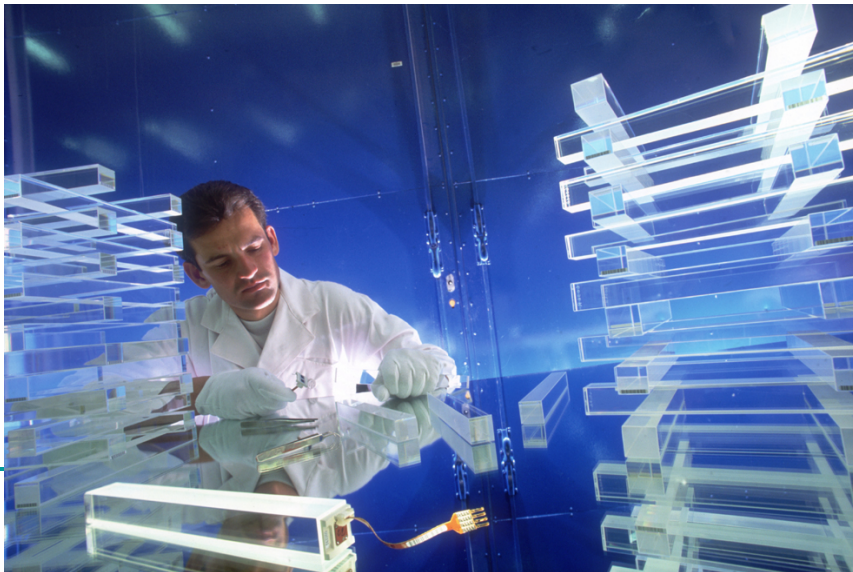
- ionization makes e-h pairs with electrons excited to the conduction band
- the e-h become loosely bound to each other forming an *exciton*
- the exciton moves together in the crystal; impurities or defects (w/o activator) provide a site for recombination
- example of exciton luminescence
 - BGO (bismuth germanate $\text{Bi}_4\text{Ge}_3\text{O}_{12}$)



BGO from Shanghai
Institute of Ceramics

Self-Activated Crystals

- chemically pure crystal has luminescence centres (probably interstitial) due to stoichiometric excess of one of the constituents
- example: PbWO_4 and CdWO_4
 - extra tungstate ions are the activator centres



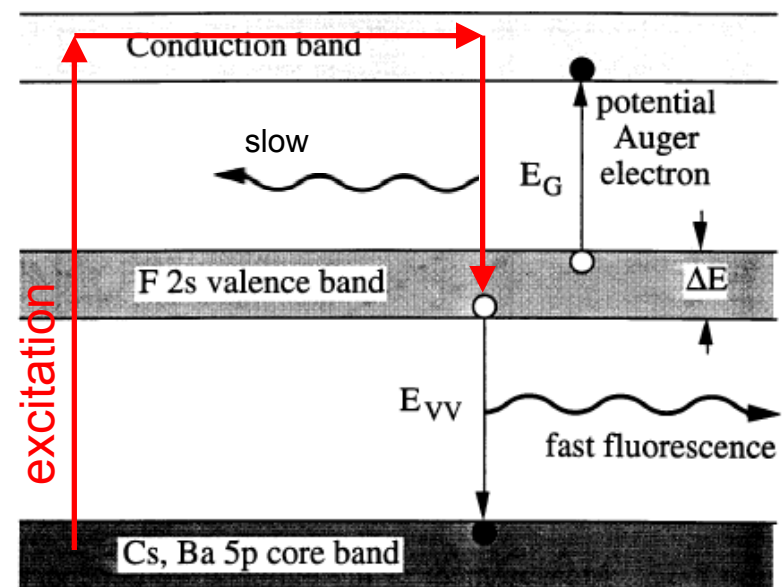
PbWO_4 crystals for the CMS ECAL
from Wikipedia

Core-Valence Luminescence

BaF₂ photo from
Saint-Gobain
Crystals



- in BaF₂, core electrons (mainly Ba²⁺) aren't that tightly bound and get excited to the conduction band
- a valence band electron (mainly F⁻) very quickly combines with the core hole
- need $E_{VV} < E_G$, else an Auger electron would be emitted instead of a photon
- slow decay from conduction to valence band



from S.E. Derenzo

Comparison of Inorganic Crystals

Parameter:	ρ	MP	X_0^*	R_M^*	dE/dx	λ_I^*	τ_{decay}	λ_{max}	n^{\natural}	Relative output [†]	Hygroscopic?	$d(\text{LY})/dT$
Units:	g/cm^3	$^{\circ}\text{C}$	cm	cm	MeV/cm	cm	ns	nm				$\%/^{\circ}\text{C}^{\ddagger}$
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	230	410	1.85	100	yes	~ 0
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	9	no	-1.6
BaF ₂	4.89	1280	2.03	3.10	6.6	30.7	630 ^s 0.9 ^f	300 ^s 220 ^f	1.50	21 ^s 2.7 ^f	no	-2 ^s $\sim 0^f$
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1300	560	1.79	45	slight	0.3
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	35 ^s 6 ^f	420 ^s 310 ^f	1.95	5.6 ^s 2.3 ^f	slight	-0.6
PbWO ₄	8.3	1123	0.89	2.00	10.2	20.7	50 ^s 10 ^f	560 ^s 420 ^f	2.20	0.1 ^s 0.6 ^f	no	-1.9
LSO(Ce)	7.40	2070	1.14	2.07	9.6	20.9	40	420	1.82	75	no	~ 0
GSO(Ce)	6.71	1950	1.38	2.23	8.9	22.2	600 ^s 56 ^f	430	1.85	3 ^s 30 ^f	no	-0.1

from Particle Data Group, Review of Particle Detectors

* Numerical values calculated using formulae in this review.

[‡] Refractive index at the wavelength of the emission maximum.

[†] Relative light yield measured with a bi-alkali cathode PMT.

[‡] Variation of light yield with temperature evaluated at room temperature.

f = fast component, *s* = slow component

CaF₂(Eu) 3.18

CdWO₄ 7.9

LaBr₃(Ce) 5.08

940 435 1.47 50 no

14000 475 2.3 40 no

16 380 1.9 165 yes

from Saint-Gobain Crystals

Comparison of Emission Spectra with PMT and Photodiode Spectral Response

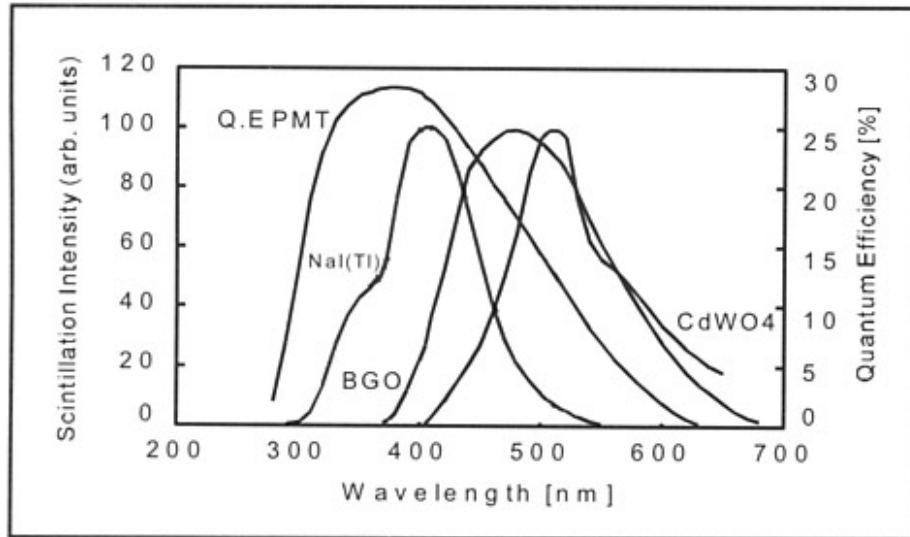


Fig. 3.1 Emission spectra of NaI(Tl), BGO and CdWO₄, scaled on maximum emission intensity.

from http://www.geocities.com/wnes_crystal/crystals.htm

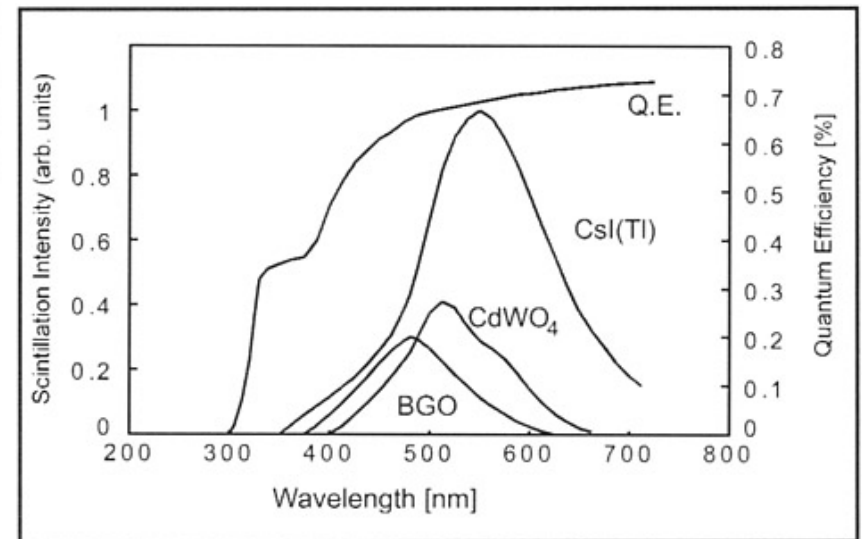


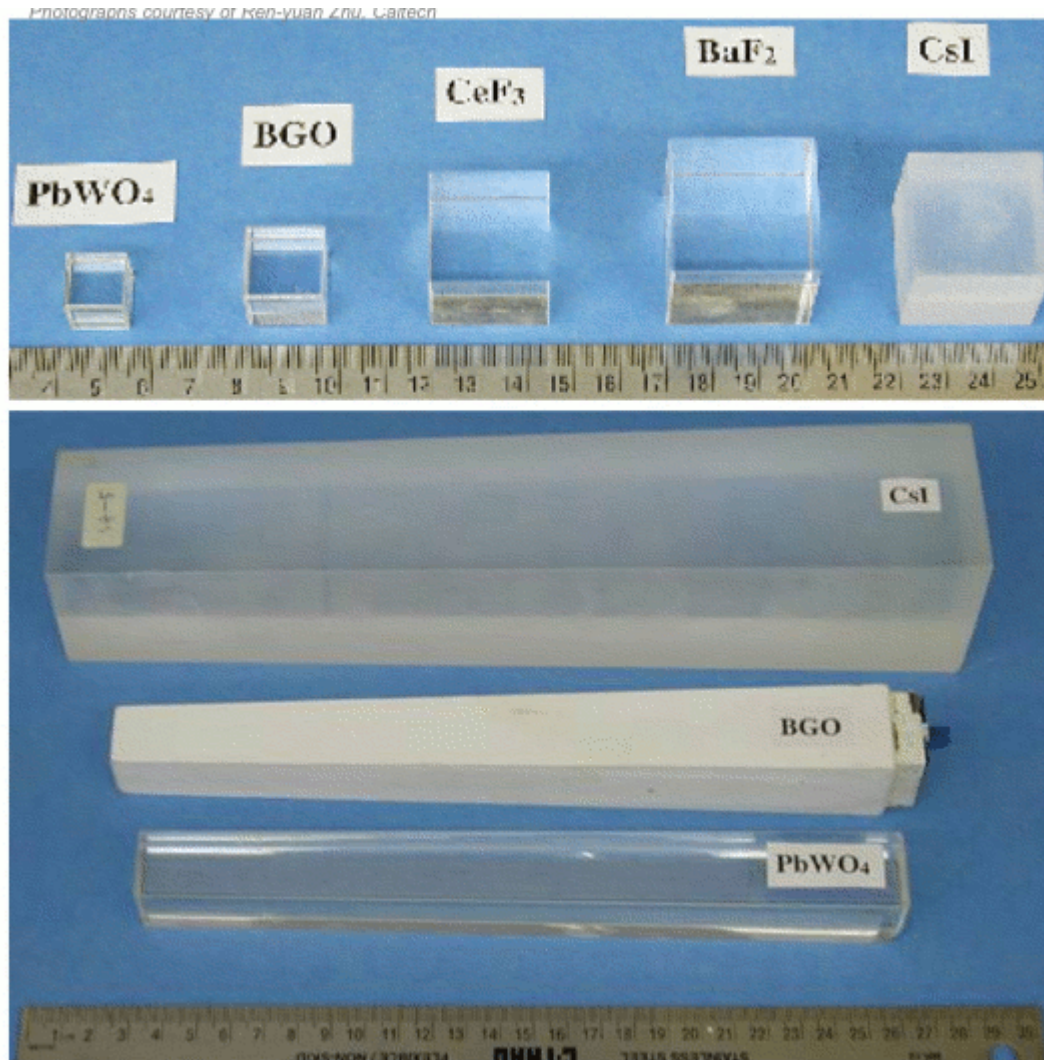
Fig. 4.3 Quantum efficiency curve of a silicon photodiode together with the emission spectrum of CsI(Tl), CdWO₄ and BGO.

from http://www.scionixusa.com/pages/navbar/read_out.html

Crystal Comparison Notes

- light yield compared to NaI(Tl) is over the spectral response range of bi-alkali PMT
 - some crystals emit at longer wavelengths and are better matched to Si photodiode spectral response
 - e.g. CsI(Tl) with a photodiode would be 145% of NaI(Tl)
 - CdWO₄ is very slow but has low Th and Ra contamination (usually) and is thus good in low-background counting applications
 - also has very small afterglow
 - LaBr₃ is relatively new and looks appealing
 - high light output
 - fast decay time
 - **however**, has ¹³⁸La (0.09% naturally-occurring) β, γ background
-

Radiation Length Photo Comparison



from Imperial College CMS group web page...photo from Ren-Yuan Zhu (Caltech)

Afterglow

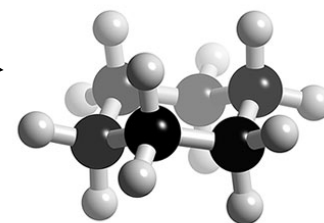
- scintillation light that is given off after several milliseconds (phosphorescence)
 - caused by impurities or defects that create traps or metastable states with long lifetimes
 - BGO, GSO(Ce), PbWO_4 , CdWO_4 tend to have small afterglow $\sim 0.005\%$ after 3 ms
 - the doped alkali halides like NaI(Tl) and CsI(Tl) can be quite high, $\sim 0.1-5\%$ after 3 ms
-

Organic Scintillators

- the scintillation mechanism is determined by the chemistry and physics of the benzene ring
 - an organic scintillator will thus scintillate whether it's in a crystal form, is a liquid, a gas, or imbedded in a polymer
 - all organic scintillators in use employ aromatic molecules (i.e. have a benzene ring)
 - we'll examine the photophysics of aromatic molecules in detail...
-

Carbon Bonds

- carbon: $1s^2 2s^2 2p^2$ electronic ground state
- carbon bonds: $1s^2 2s^1 2p^3$ and the 2s and 2p orbitals are hybridized
 - sp^3 hybridization is tetrahedral (e.g. diamond, methane, cyclohexane)
 - not luminescent
 - sp^2 hybridization is planar
 - p_z orbital is unchanged
 - double-bonded carbon (e.g. ethylene, benzene)
 - is luminescent and the basis of organic scintillators
 - sp hybridization is linear
 - triple-bonded carbon (e.g. acetylene)
 - also luminescent

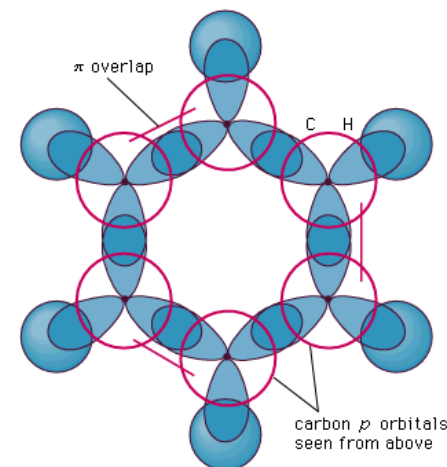


from 3Dchem.com

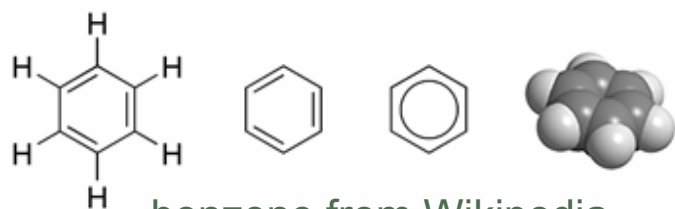
σ -Bonds and π -Bonds

from Encyclopedia Britannica web

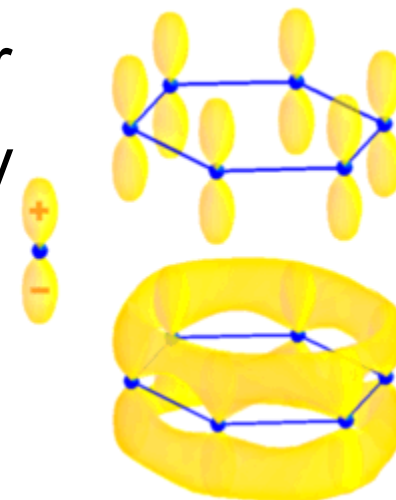
- σ -bonds are in the plane, bond angle 120° , from sp^2 hybridization
- π -orbitals are out of the plane
 - in the benzene ring (and other carbon double bonds) they overlap each other
 - result is the π -electrons are completely delocalized



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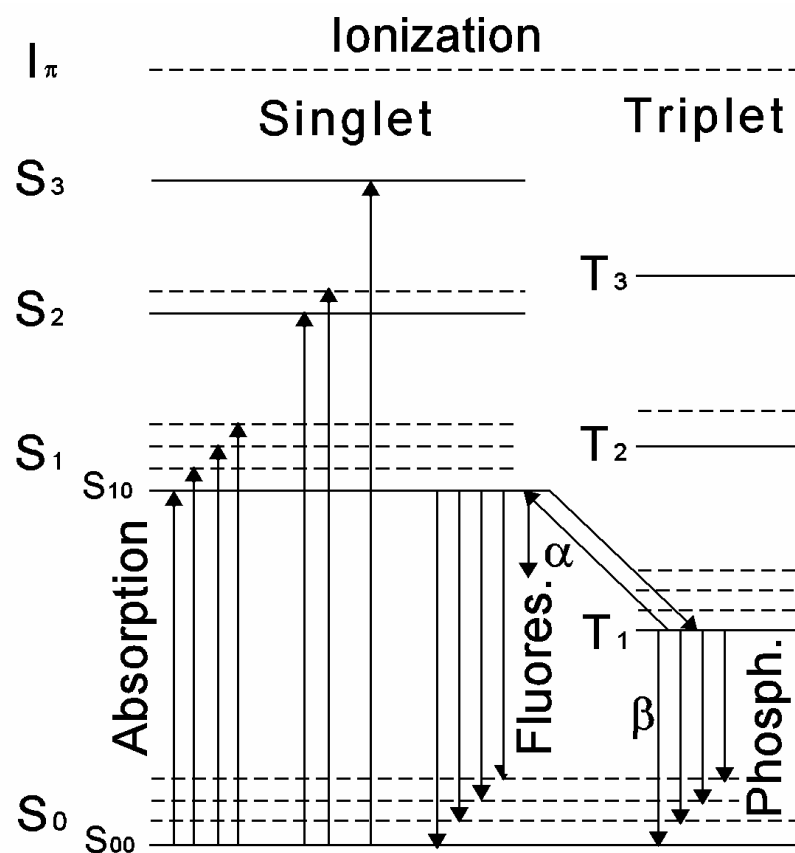
benzene from Wikipedia



from <http://www.monos.leidenuniv.nl/smo/index.html?basics/photophysics.htm>

π -Electronic States

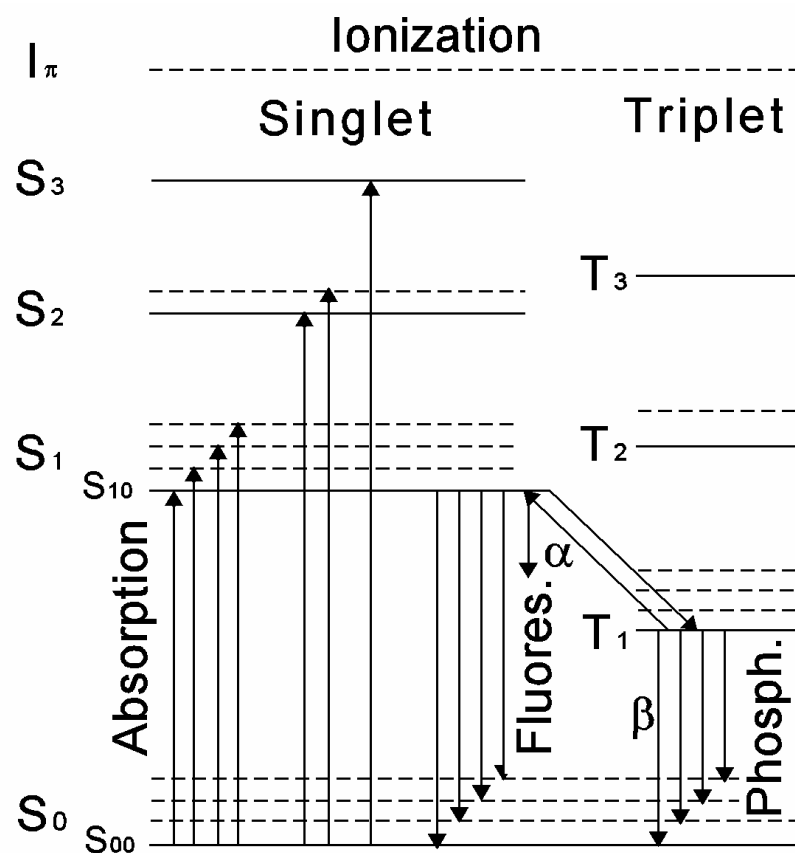
- theory of π -electron excited states uses a “perimeter free-electron model”, with electrons going around the ring in both directions, spin up and down
- absorption spectroscopy confirms the theory
- the π -electronic states diagram can be deduced from theory and spectroscopy
 - has vibrational sub-levels (e.g. S_{10} , S_{11}) with ~ 0.16 eV spacing
- after absorption of a photon or excitation by ionization, the molecule undergoes vibrational relaxation (or internal conversion or degradation) to S_{10}



from M. Kobayashi (KEK), adapted from J.B. Birks

Scintillation in Organic Molecules

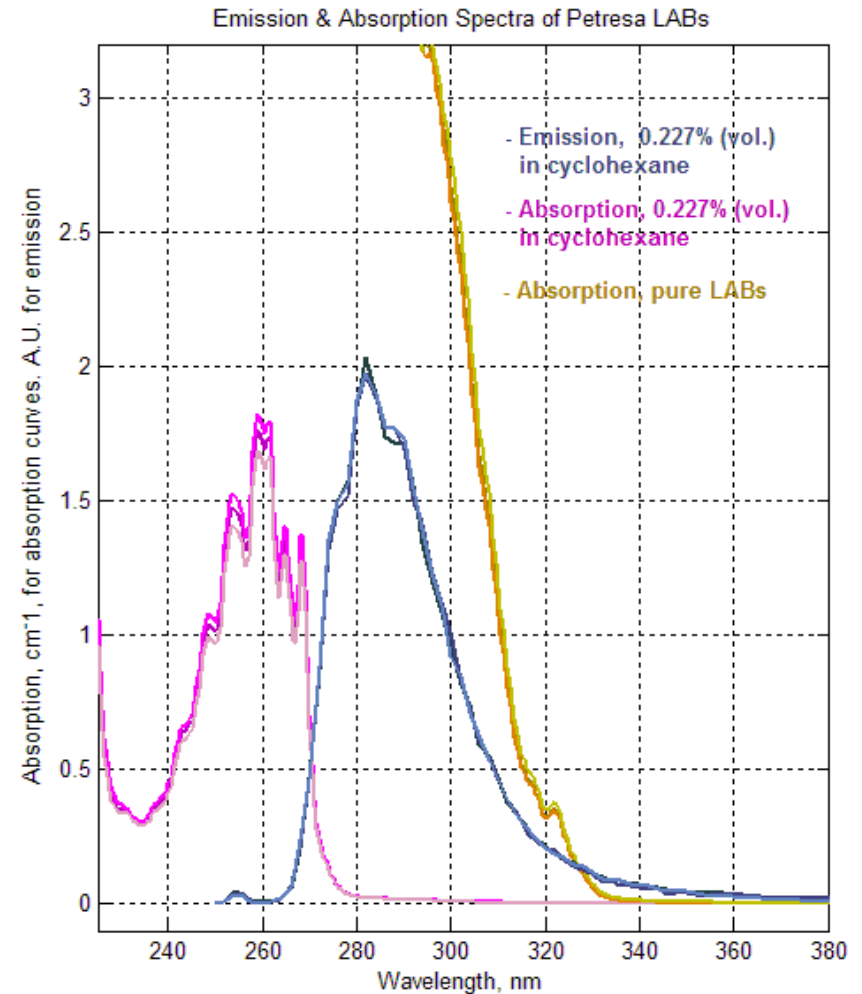
- the excited S_{10} state decays radiatively to vibrational sub-levels of the ground state
- the S_{10} lifetime is \sim ns
- thus the fluorescence emission spectrum is roughly a “mirror image” of the absorption spectrum (same spacing)
- emitted photons have less energy than S_{00} - S_{10} – that’s the important **Stokes shift**
- there is no S_2 - S_0 emission because internal conversion is efficient and fast \sim ps
- there are σ -electronic excited states too; but they are at higher energies above S_3



from M. Kobayashi (KEK), adapted from J.B. Birks

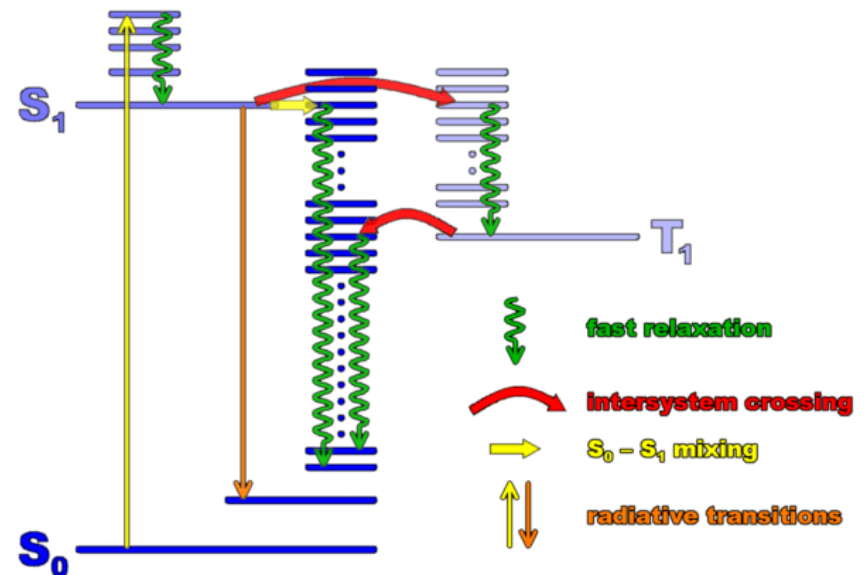
Mirror Image: Absorption and Emission

- compare the **absorption spectrum** with the **emission spectrum**
- individual vibrational states are thermally broadened and smear together



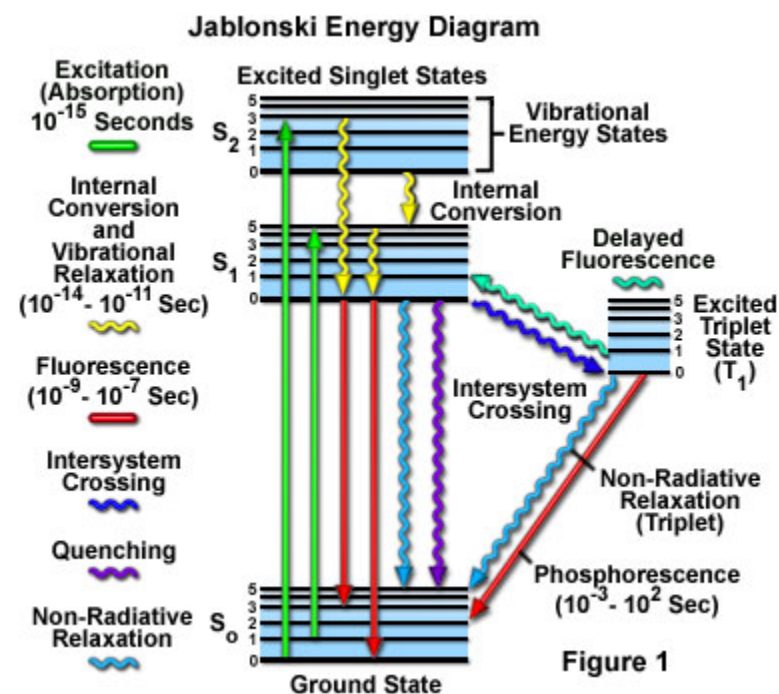
Competing Processes

- non-radiative decay
 - due to overlap of an S_0 vibrational state with S_1
- ratio of the radiative rate to the total decay rate (radiative plus non-radiative) is the *fluorescence quantum yield*
- quantum yields of 0.8 or greater are typical for “good” scintillators



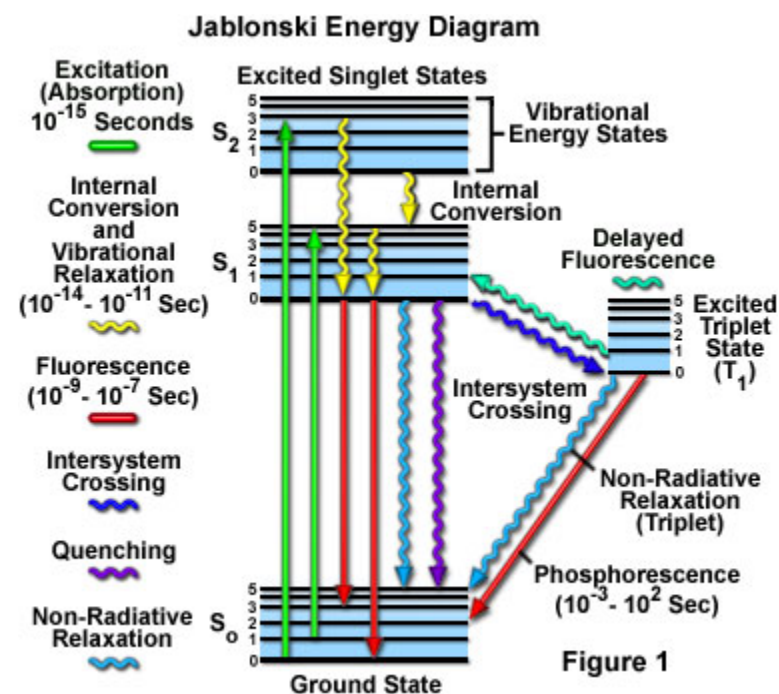
Competing Processes cont'd

- an intersystem crossing can occur, populating the triplet state
 - S_0 - T_1 and T_1 - S_0 cannot occur directly due to angular momentum and parity selection rules
- T_1 has a long lifetime since decay to the S_0 is forbidden
 - this is phosphorescence
- delayed fluorescence from the triplet can also occur
 - $T_1 + T_1 \rightarrow S_1 + S_0 + \text{phonons}$
 - $\sim \mu\text{s}$



Aside: Triplet Lower than Singlet?

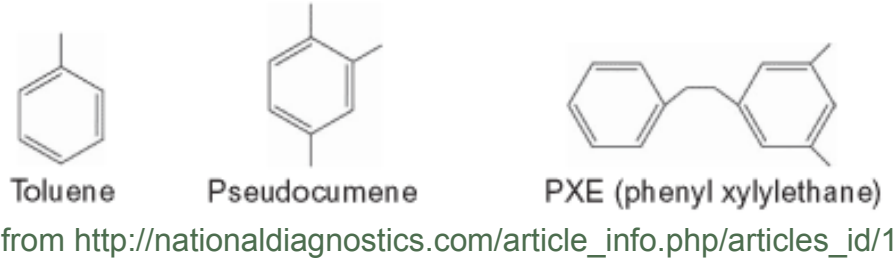
- why is the triplet T_1 state lower in energy than the singlet S_1 state?
 - it's experimentally observed: phosphorescence is at longer wavelengths than fluorescence
- Hund's Multiplicity Rule: for the same configuration the lower energy state is the one which has the higher total spin
 - the common explanation for Hund's rule is that states with parallel spins are more spatially separated and thus the electron-electron repulsion is less, and the energy is thus lower
 - atomic quantum calculations show this is not true; the real reason is that the antisymmetric nature of the triplet state contracts the 2s orbital radius resulting in more tightly-bound electrons to the nuclei and a lower energy



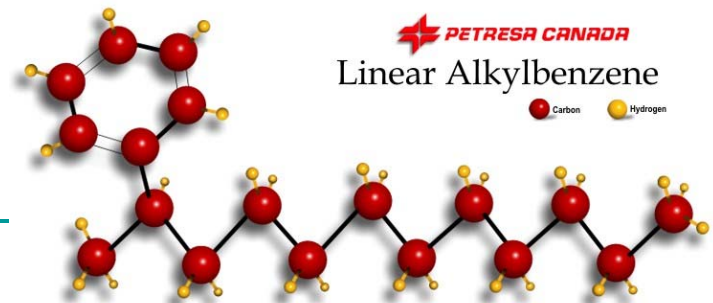
Organic Liquids

- **any aromatic organic solvent is a scintillator**
 - e.g. benzene, xylene, pseudocumene (1,2,4-trimethylbenzene)
 - **to improve the performance, a scintillating solute is dissolved in the solvent – this is called the fluor**
 - e.g. PPO (2,5-diphenyloxazole), p-terphenyl, butyl-PBD
 - typically g/L quantities
 - **this accomplishes the following:**
 - efficient non-radiative transfer of excitation energy from the solvent to the fluor
 - high fluorescence quantum yield of the fluor
 - emission of fluor at even longer wavelengths compared to the absorption of the solvent, further reducing self-absorption
 - typically fast decay times
 - **if desired a secondary wavelength shifter (WLS) can be added**
 - e.g. bisMSB, POPOP
 - absorbs the light from the fluor and re-emits it at longer wavelengths that match the spectral response of the light detector
 - typically 10's mg/L quantities
 - **the whole cocktail can be diluted in an optically-inert liquid**
 - e.g. mineral oil, dodecane
 - usually done for chemical reasons, though good for transparency too
-

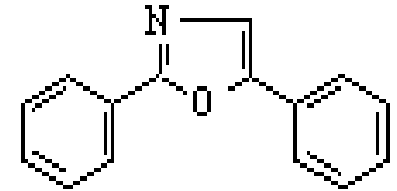
Solvents



- pseudocumene is common
 - used in KamLAND, Borexino, Palo Verde, MACRO, many commercial liquid scintillator cocktails
- safer solvents are being used (especially in biology applications)
 - PXE has density 0.985
 - DIN is in many commercial cocktails, miscible with water
 - **however** absorption is higher so less suited for large detectors
 - LAB (linear alkylbenzene)
 - developed by SNO+ as a scintillator (solvent) for nuclear/particle physics experiments; we're the first experiment to propose using LAB
 - high flash point, low toxicity
 - high light yield (about high as pseudocumene-based liquids)
 - excellent transparency
 - compatible with plastics like acrylic
 - cheap



Binary Mixtures and the Fluor



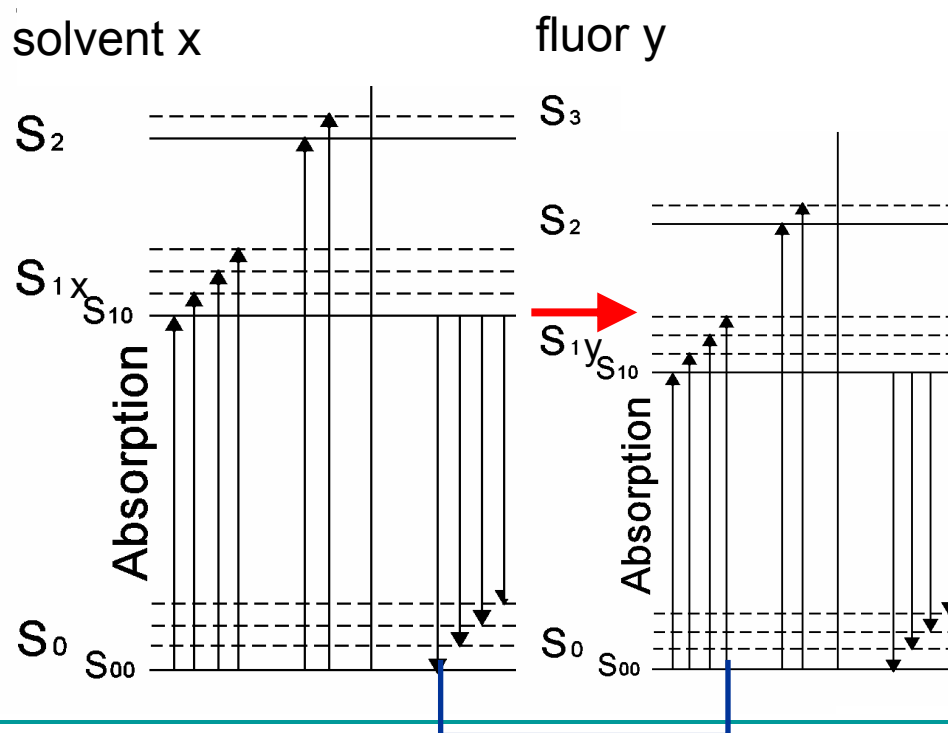
PPO or 2,5-diphenyloxazole

- the solvent molecule x is excited, relaxes to S_{1x}
- either by radiative or non-radiative transfer, the S_{1y} in the fluor molecule y is excited
 - radiative transfer is absorption and re-emission by the fluor
 - the emission spectrum of the solvent chosen to overlap the absorption spectrum of the fluor
 - S_{1y} is thus slightly lower in energy than S_{1x}
- this has to occur preferentially over non-radiative de-excitation of the solvent molecules S_{1x}
- efficient non-radiative transfer depends on the concentration of fluor in the binary mixture
 - occurs by solvent-solvent dipole resonance interaction (**Förster energy transfer**) or by thermal diffusion of excited solvent molecules in a liquid
 - occurs by **Förster energy transfer** between the same or adjacent polymer chains in the plastic

Energy Transfer: Solvent-Fluor

red: efficient non-radiative transfer is desired

aside: fluor-WLS energy transfer can be *radiative* because of the high quantum yield of the fluor and small WLS concentrations used to maximize transparency



blue: radiative transfer works; reduced by solvent fluorescent quantum yield

Determining the Efficiency of Energy Transfer

Method 1 (fluorescence emission method): measure the fluorescence excitation and emission of PPO-LAB solution; excitation at 318 nm (LAB excitation), integrate emission range from 340-550 nm (PPO emission)

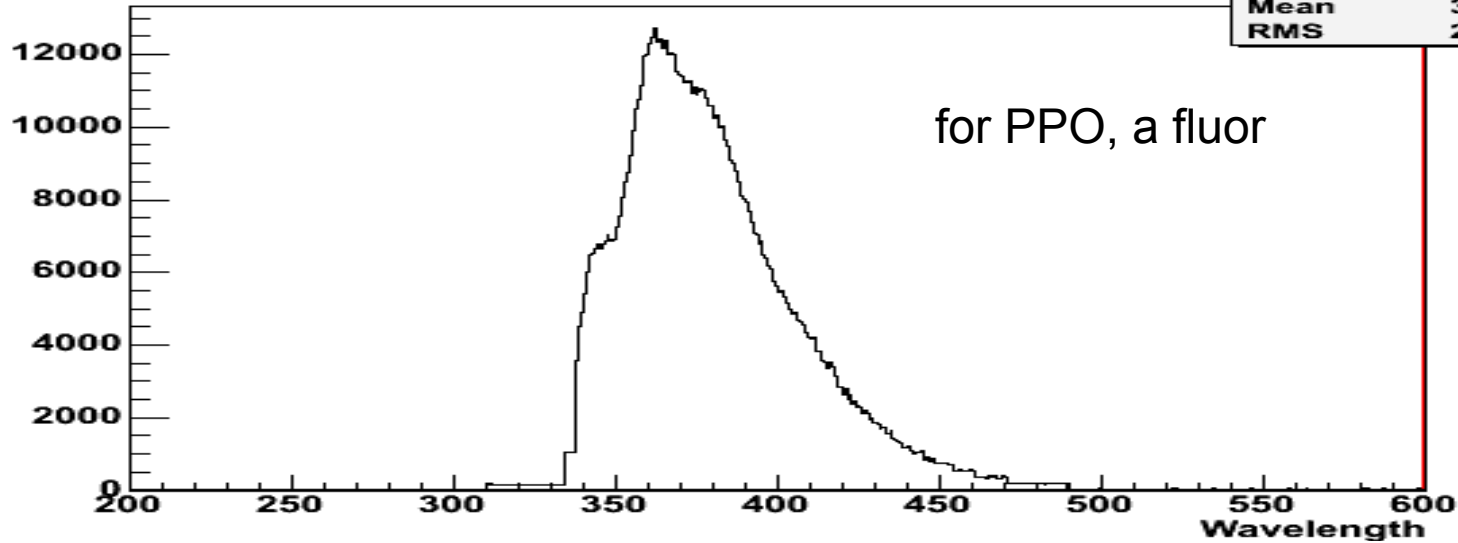
Method 2 (decay time method): excitation at 250 nm, emission 360 nm, measure the decay times of PPO-LAB solution, compare to the decay time of pure PPO

LAB-PPO energy transfer efficiency

PPO [g/L]	Method 1	Method 2
32	n/a	90.7%
4	80%	80%
2	72%	73%
1	60%	61%
0.5	46%	55%
0.25	35%	47%
0.1	23%	n/a
0.02	5.6%	n/a

Emission: Fluor and Wavelength Shifter

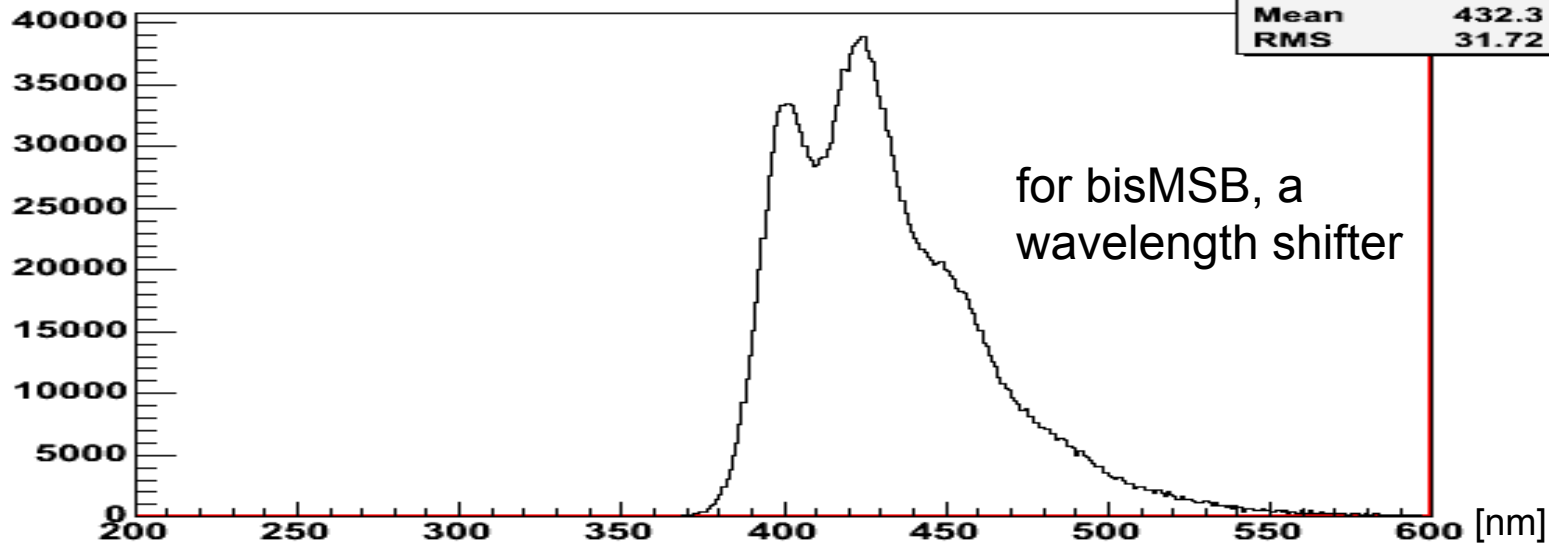
Primary Scintillation Spectrum



PRI	
Entries	1080235
Mean	380.4
RMS	29.64

for PPO, a fluor

snoman_3

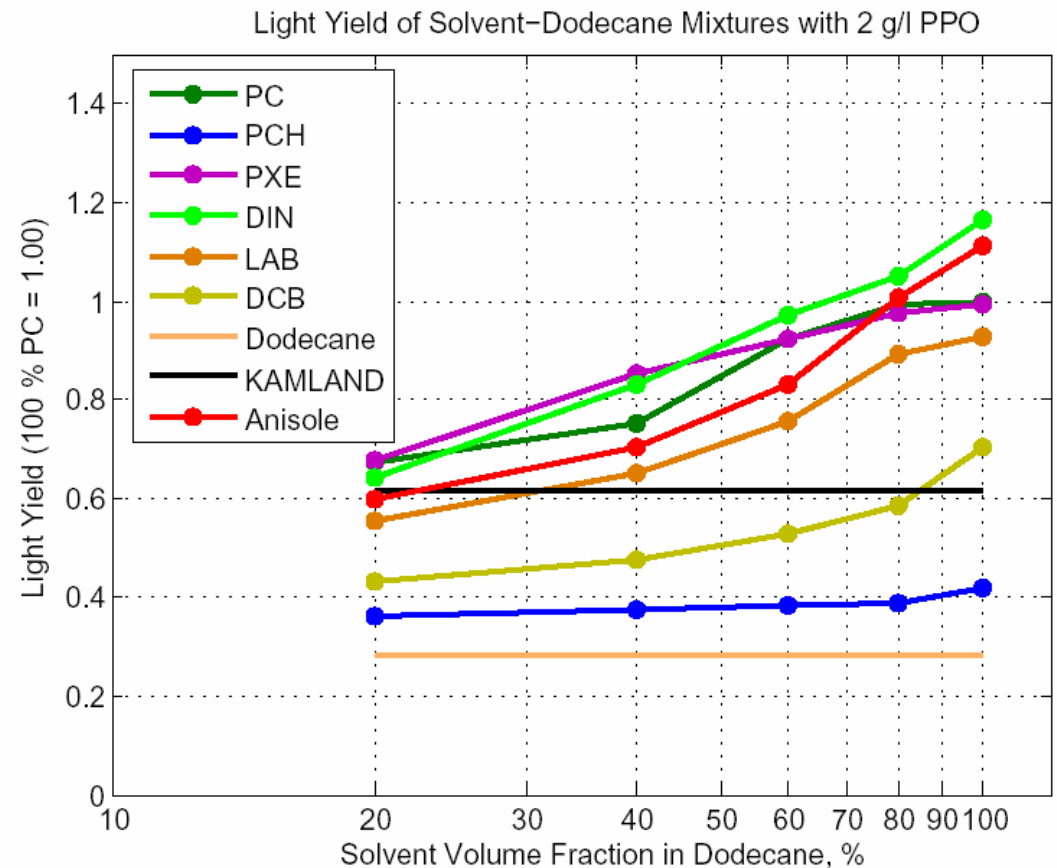


snoman_3	
Entries	2403871
Mean	432.3
RMS	31.72

for bisMSB, a wavelength shifter

Diluting Liquid Scintillator

- diluting the cocktail in mineral oil or dodecane reduces the light output
- but note that 20% solvent concentration still exhibits ~70% of the light output
- it's not just the fraction of the excitation that was imparted to the solvent
- strongly suggests non-radiative energy transfer takes place between the dodecane and the solvent and/or fluor

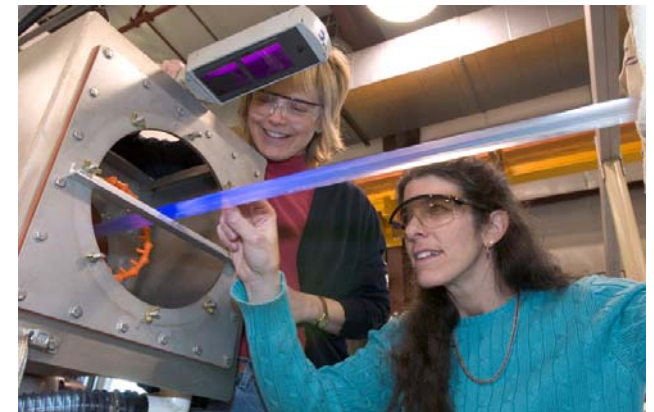


Comparing Liquid Scintillator to Inorganic Crystals

- decay time:
 - PPO intrinsic 1.6 ns versus NaI(Tl) 230 ns
 - light yield:
 - PC-PPO 14,000 photons/MeV versus NaI(Tl) 40,000 photons/MeV
 - density:
 - organic liquids C,H with $\rho < 1 \text{ g/cm}^3$ versus many high-Z crystals with $\rho > 5 \text{ g/cm}^3$
-

Plastic Scintillator

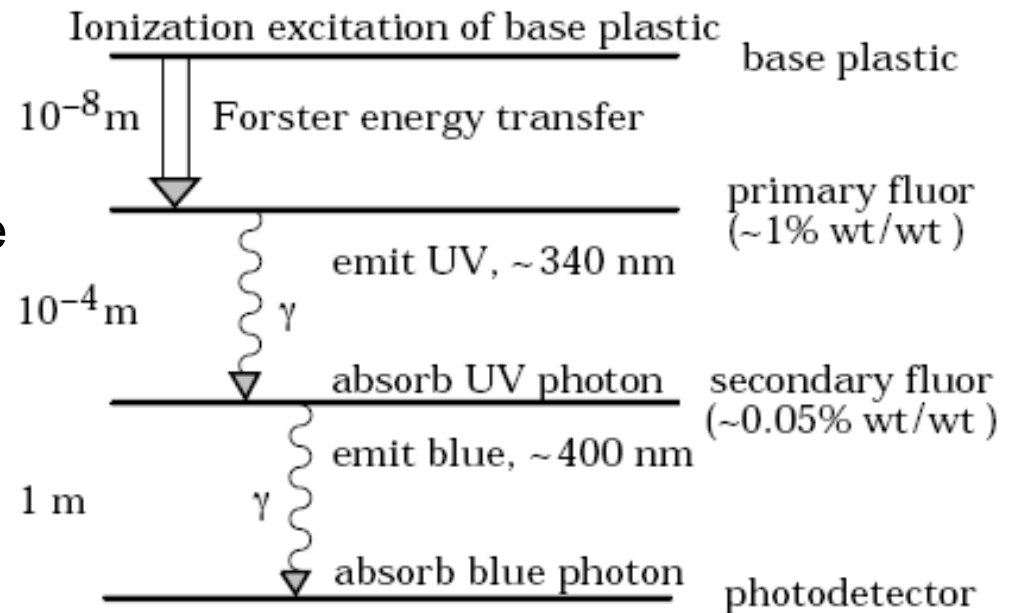
- very common in nuclear and particle physics
- polymer base is typically PVT (polyvinyltoluene) or polystyrene (PVT-based slightly higher light yield)
 - aliphatic plastics (e.g. acrylic) can be used also, but have half the light yield of aromatic plastics
- primary solute is dissolved in the plastic
 - e.g. PBD, p-terphenyl, PBO
- secondary wavelength shifter
 - e.g. POPOP c1ccc(cc1)-c2oc(=N)cc2-c3ccc(cc3)-c4oc(=N)cc4-c5ccccc5
 - e.g. BBQ
- same scintillation mechanism



extruded plastic scintillator
for MINERvA from Wikipedia

Scintillation in a Plastic

- high concentrations of fluor shorten the decay time and increase the light yield
- at 1% fluor concentration, the average distance between a fluor molecule and an excited base is 10 nm, less than a wavelength of light
- Förster dipole-dipole resonance energy transfer efficiently excites the fluor with a faster decay time and high quantum yield



from Particle Data Group, Review of Particle Detectors

Plastic Scintillator: Advantages and Disadvantages

- reliable, robust, cheap, easy to fabricate into desired shapes
- can be used to detect neutrons by detecting proton recoils (as for a liquid scintillator)
- **drawbacks:**
 - subject to aging
 - degrades upon exposure to some chemicals (e.g. oils, solvents, fingerprints)
 - suffers radiation damage
 - not resistant to high temperatures
 - surface crazing affects light propagation because a plastic scintillator usually relies on total internal reflection at the surface



Care of Plastic Scintillator

Jeff Wilkes (UW) cleaning up a plastic scintillator from NSF Public Affairs web page



Comparing Plastic to Liquid

scintillator	light output	peak λ	decay constant	attenuation length	index of refraction	density [g/cm ³]
BC-400	65%	423 nm	2.4 ns	250 cm	1.58	1.032
BC-404	68%	408 nm	1.8 ns	160 cm	1.58	1.032
BC-416	38%	434 nm	3.3 ns	400 cm	1.58	1.032
BC-428	36%	480 nm	12.5 ns	150 cm	1.58	1.032
PC-based liquid	80%	425 nm	2.5 ns		1.505	0.877
30% PC diluted in mineral oil	60%	425 nm	3 ns	>500 cm	1.48	0.86
LAB-based	75%	425 nm	3.5 ns		1.47	0.87



from Saint-Gobain Crystals

note: values for plastics are for commercial products while liquid scintillator cocktails are representative values that can be adjusted by selecting the fluor, the wavelength shifter and their concentrations

note: light yield is quoted as a fraction of anthracene, which is 17,400 photons/MeV

Scintillating Glass Blocks

- glass doped with an activator scintillates like an inorganic crystal
 - e.g. Ce-doped glass
- however, energy transfer to the activator centre is much less efficient without the crystal lattice
- light yield is much reduced compared with an inorganic crystal, less than few% of NaI(Tl)
- decay time: ~tens ns
- short radiation length is possible by adding lead
- inexpensive, physically and chemically resistant
- ${}^6\text{Li}$ glass used for slow neutron detector $n + {}^6\text{Li} \rightarrow \alpha + t$

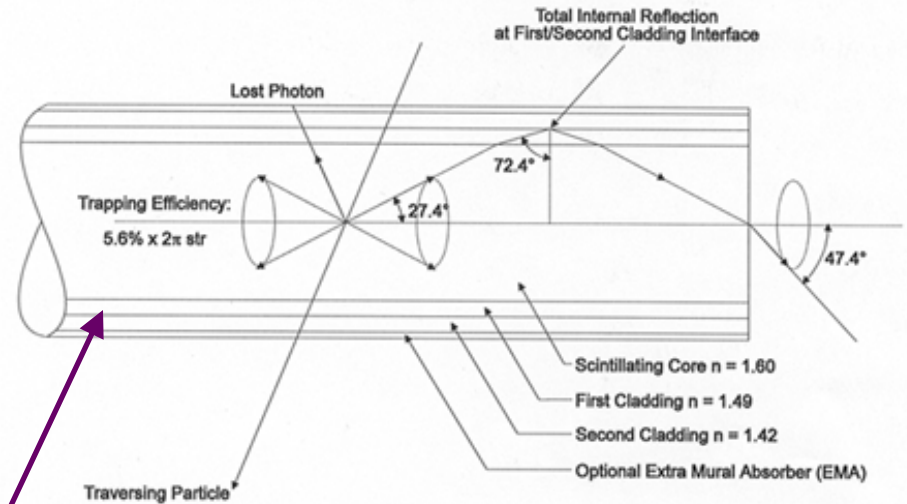


lead glass Čerenkov radiator from Fermilab Charmonium E835 in Museum of Modern Art in New York City

Scintillating Fibres

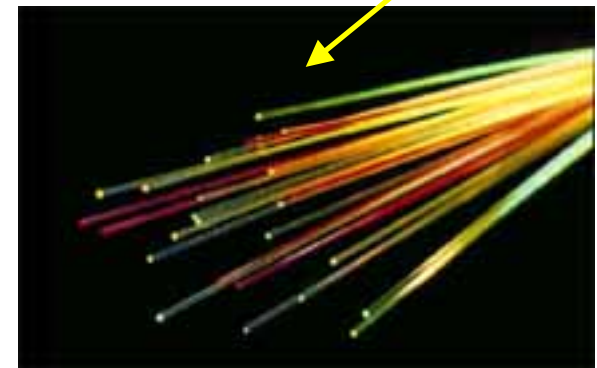
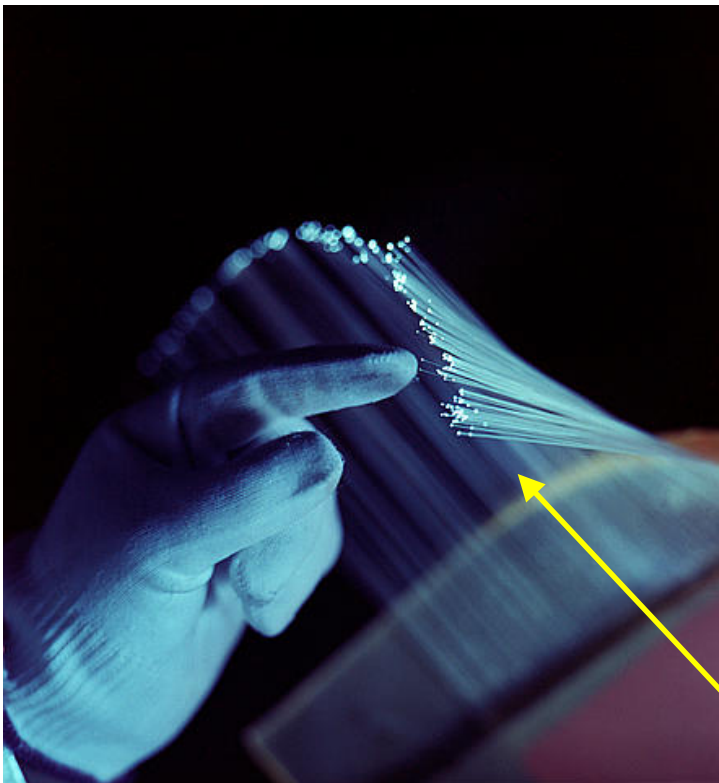
- the fibre core is
 - glass with activator
 - polystyrene with fluor

A Typical Round Multi Clad Scintillating Fiber



PMMA first cladding
fluorinated PMMA second cladding

polystyrene core
fibres from Saint-Gobain Crystals



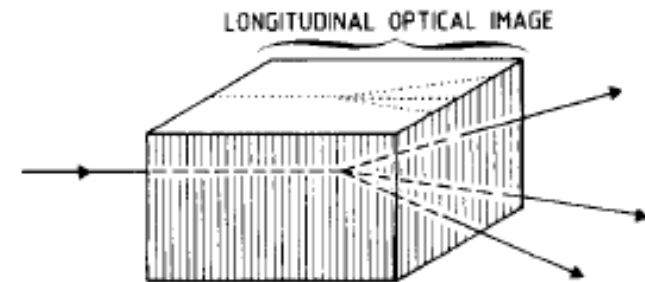
glass fibers from Pacific Northwest National Lab

Typical SCIFI Performance

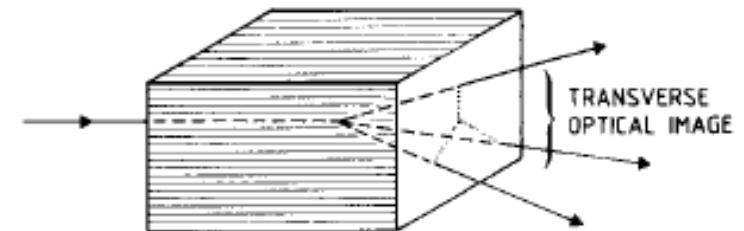
- isotropic light that is collected
 - single-clad: ~6%
 - double-clad: ~10%
- minimum ionizing particle passes through a 1 mm fibre
 - 2 MeV/cm
 - 10,000 photons/MeV
 - thus ~2000 photons emitted
- only 200 are transported down the fibre
- 95% lost due to attenuation (depends on length)
- out the end, the DØ SCIFI Tracker (0.8 mm diameter fibre) gets about 9 photoelectrons (with an 85% quantum efficiency detector)

scintillating fibre bundle as a particle tracker

b) SCINTILLATING FIBRE BUNDLE (FIBRES PERPENDICULAR TO TRACK)

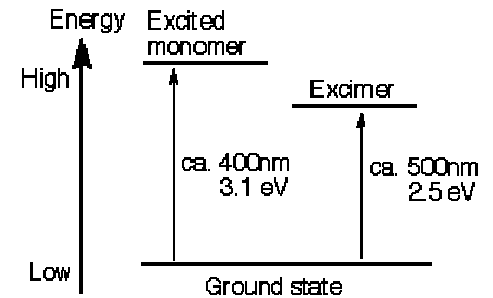


c) SCINTILLATING FIBRE BUNDLE (FIBRES PARALLEL TO TRACK)



from M. Atkinson et al.

Noble Gases and Liquids



- scintillation mechanism is again different
- noble gases/liquids are monatomic but excited atoms can form dimers (excited dimer or excimer)
 - e.g. Ar_2^*
- the excited dimer is either in a singlet or triplet state
 - singlet state is fast (6 ns for argon)
 - triplet state is slow (1.6 μs for argon)
- it decays by photon emission with photon energy less than what's needed to excite the monomer
 - hence, transparent to its own scintillation light
- high light yield: e.g. 40,000 photons/MeV for argon

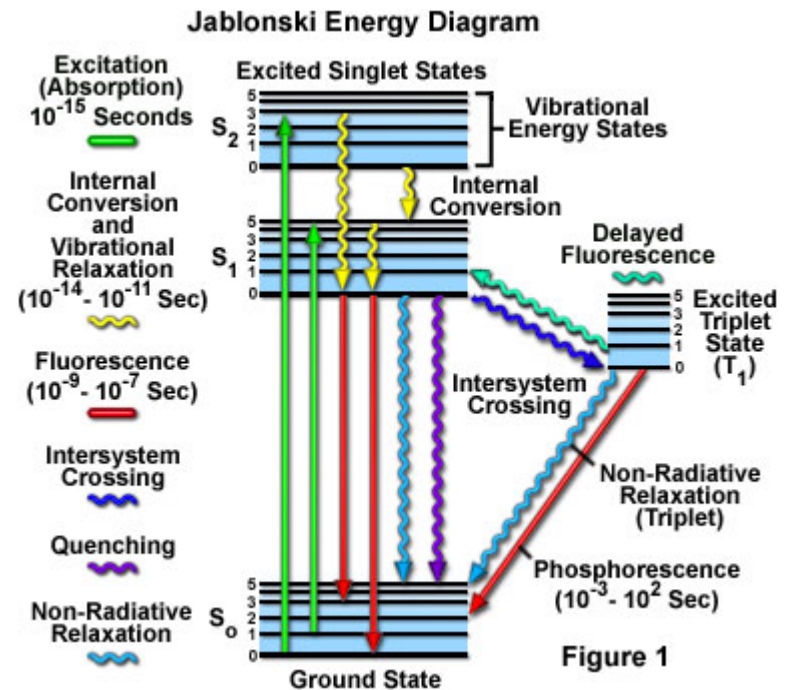
I won't discuss noble gases or liquids further since there will be lectures on this topic.

Additional Considerations

- quenching, **linearity** and **pulse-shape discrimination (PSD)** are related properties
 - PSD is the ability to distinguish between different particles exciting the scintillation by the shape of the light pulse
 - these properties can be considered, in general, for all types of scintillators
 - most of this discussion is directed at organic scintillators
-

Quenching

- quenching is an external process that de-excites the scintillator without fluorescence
 - sometimes internal non-radiative relaxation is also called quenching
- impurity quenching
 - e.g. oxygen in an organic liquid
- ionization quenching
 - high ionization density quenches the excited π -electrons
 - saturation of available luminescent centres for inorganic crystals
 - collision of excimers for noble gases/liquids and de-excitation



from <http://micro.magnet.fsu.edu/primer/techniques/fluorescence/fluorescenceintro.html>

Impurity Quenching

- presence of oxygen in an organic liquid at ppm levels can strongly quench fluorescence, especially in unitary scintillators
 - greatly reduces light yield
 - shortens lifetimes
 - oxygen and other impurities can compete with the fluor in energy transfer from the excited solvent
 - again reducing light yield
 - to combat oxygen quenching
 - increase the fluor concentration
 - deoxygenate the scintillator by bubbling with nitrogen or vacuum degassing the liquid
 - impurities in an inorganic crystal can quench the excitation, competing with activator centres
 - the obvious solution – grow pure crystals
-

Ionization Quenching

- ionization excites singlet and triplet π -electronic states
 - leading to fast fluorescence and slow delayed fluorescence from the triplet
 - results in multi-component scintillation decay time profile whereas UV excitation produces mainly single time constant fluorescence
 - high ionization density can quench the excited singlet π -electrons
 - the fast component is thus reduced for high dE/dx particles
 - picture it as overlapping excitations that interfere with each other
 - three important consequences:
 - non-linearity in energy response
 - heavy particles with higher dE/dx (e.g. α) produce less light for the same energy deposit, (by a factor of >10 for α in liquids)
 - the scintillation pulse shape (fast/slow components) is different for heavy particles, enabling pulse-shape discrimination
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Ionization Quenching – Birks' Rule

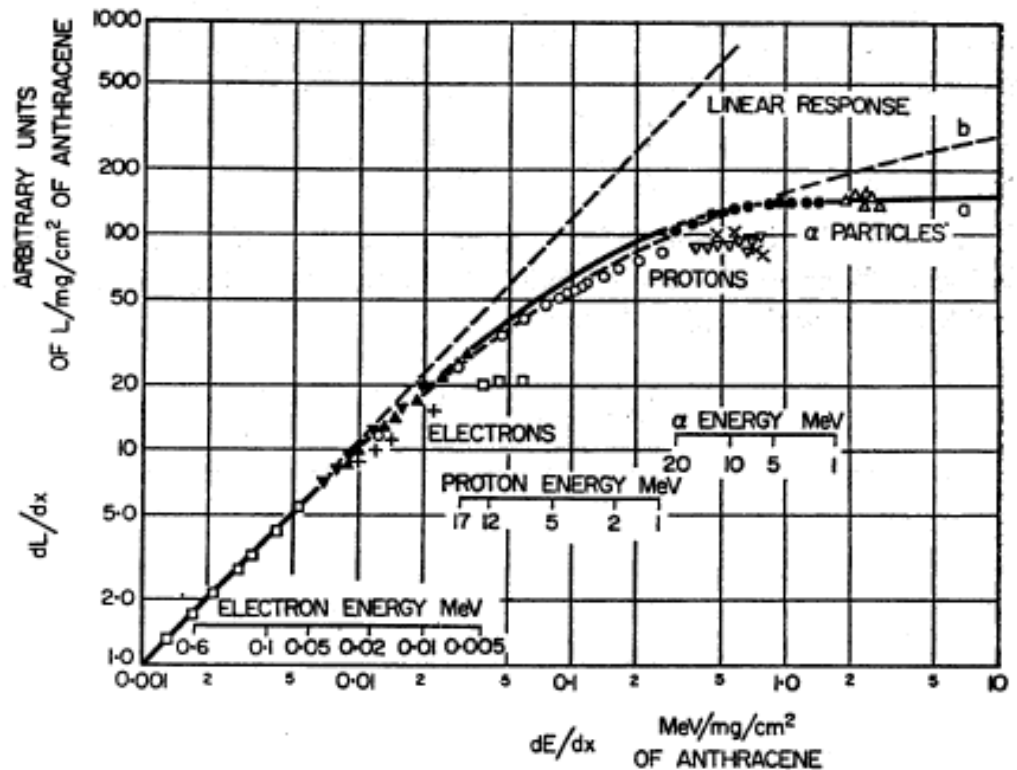
- start with linearity at low ionization density $\frac{dL}{dx} = A \frac{dE}{dx}$

- let the density of excited molecules be proportional to the ionization density $B \frac{dE}{dx}$

- let k be the fraction that is quenched $\frac{dL}{dx} = \frac{A \frac{dE}{dx}}{1 + kB \frac{dE}{dx}}$

- for small dE/dx, approaches linearity

- for large dE/dx, approaches saturation $\frac{dL}{dx} = \frac{A}{kB}$

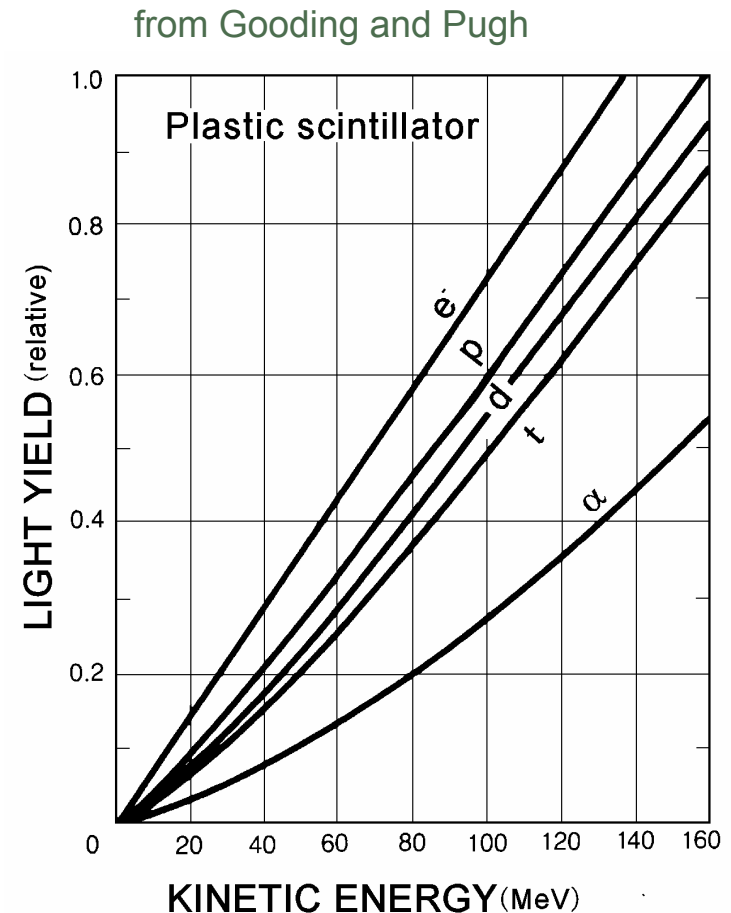


from Birks

- for any given scintillator composition, must fit the quenching data to get kB
- A is the absolute scintillation efficiency

Light Yield for Different Particles

- a significant effect in liquid and plastic scintillators because ionization quenching reduces the (majority) fast component
- only minor difference in inorganic crystals
 - e.g. 70% light output for heavy particles in a crystal compared to electrons
- noble gas/liquid light yield from different particles
 - e.g. 20-30% light output for nuclear recoils in Ar, Xe compared to electrons



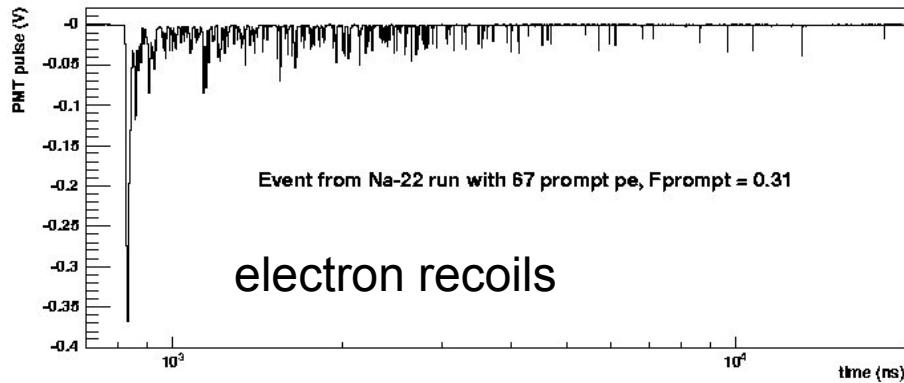
quenching factor: light output compared to that from an electron with the same energy

Pulse-Shape Discrimination

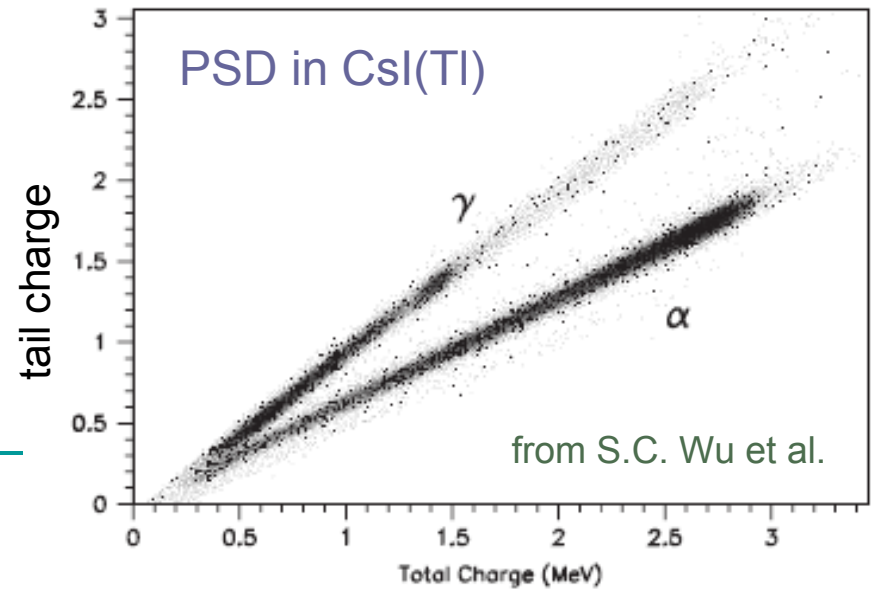
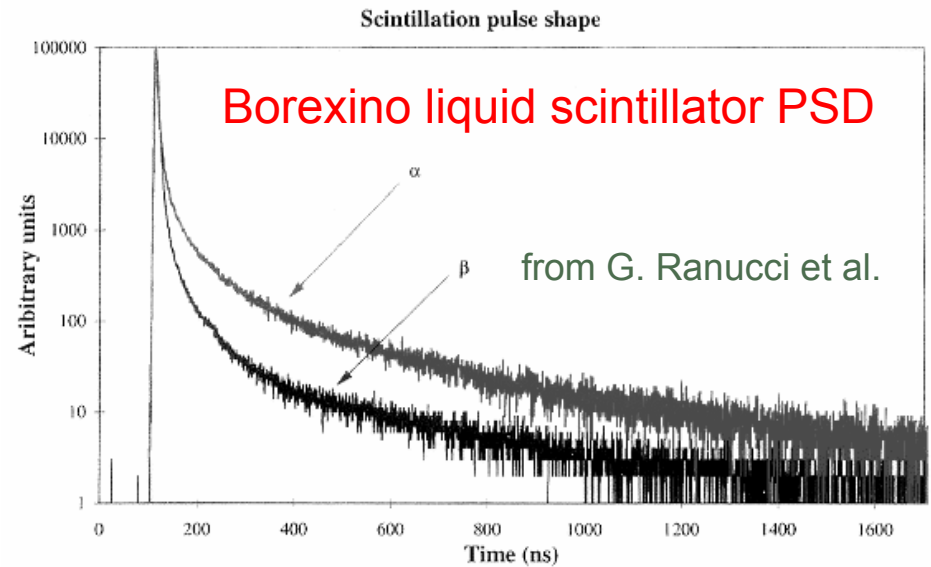
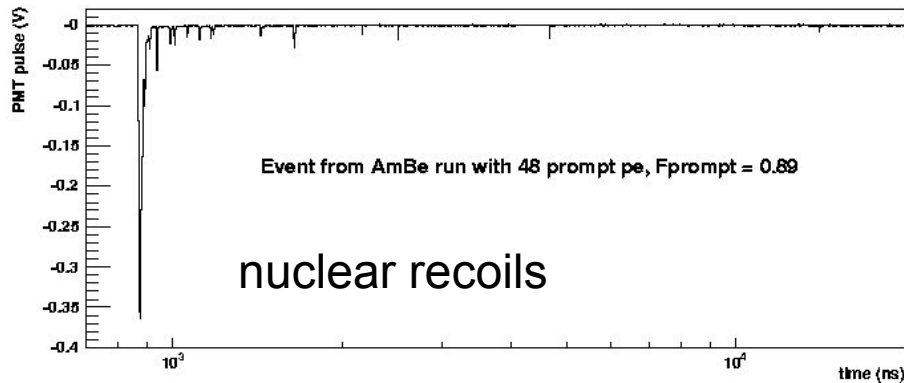
- inorganic crystals:
 - high ionization density favours exciton formation and efficient transfer to activators with fast fluorescence
 - low dE/dx has a relatively greater fraction of slow metastable states
- noble gases/liquids:
 - ionization recombines forming excited singlet dimers and high ionization density facilitates recombination
- organics:
 - high ionization density quenches fast singlet

heavy particle scintillations are faster in inorganics and noble gases/liquids while they are slower in organics!

PSD Scintillation Time Profiles



DEAP liquid argon PSD



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