Queen Mary
University of London
Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 12

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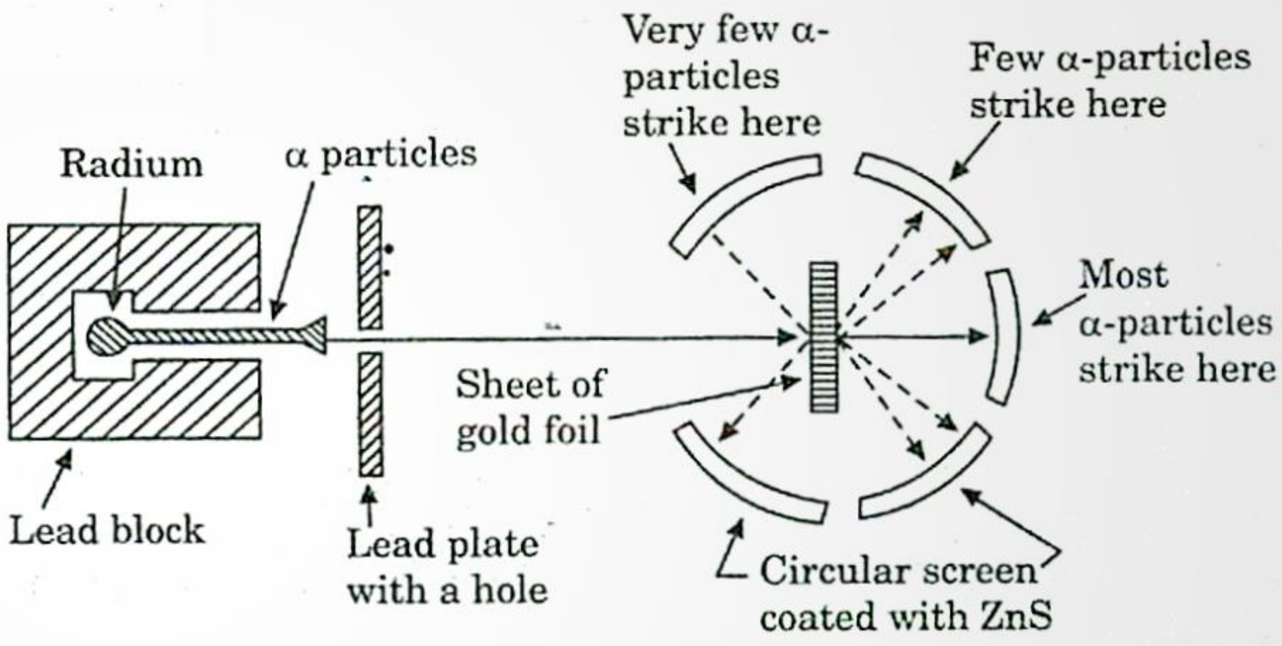
What is this lecture about?

- Scintillators
  - Basic principles
  - Important materials in current use
  - Low energy applications (spectroscopy, medicine)
  - High energy applications (calorimeters, Time-of-flight)

Earliest example

- Rutherford's scattering experiment:
  - Discovery of atomic nucleus with positive charge which holds most of its mass (1908-1913)
- Experiment:
  - Scattering of α particles on thin metal (gold) foils
  - Using microscope to count light flashes on ZnS scintillating screen
  - high efficiency (20%) but low transparency to its own light



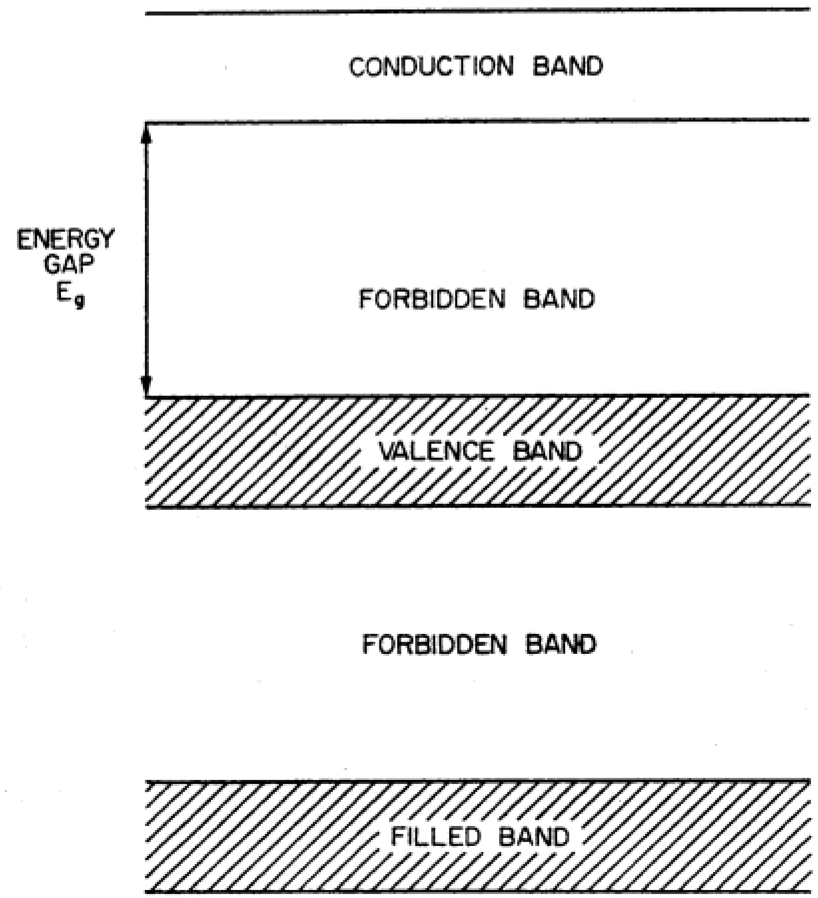
What materials can we use?

A wide range of materials are available in principle. However in practice we need to compromise based on a range of parameters:

- Speed
- Light yield (photons per MeV)
- Density
- Cost
- Typical volumes available
- Commercially viable
- Radiation tolerance
- Mechanical aspects (e.g. brittleness, thermal shock tolerance, crazing of plastics)

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.

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

$$E_{emission} < E_g$$

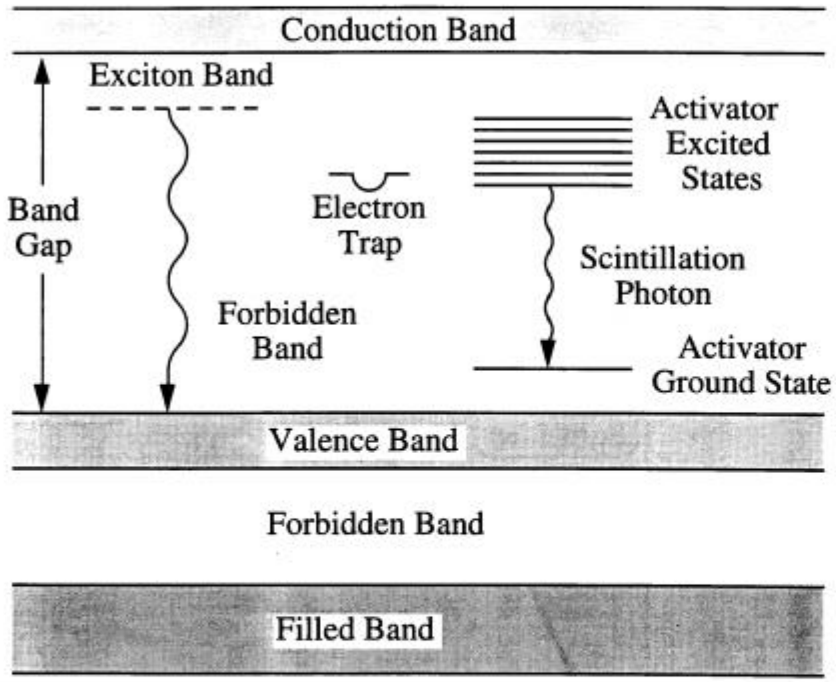
Mechanisms

Three mechanisms:

a) excitons (bound electron-hole pair)

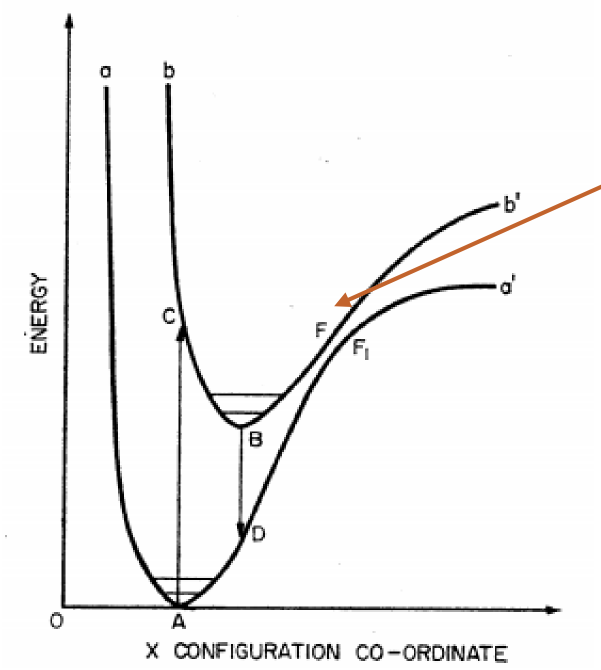
b) defects
(interstitial atoms, for example induced by heat treatment)

c) activators



Quenching of luminescence

Luminescence vs Quenching



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)

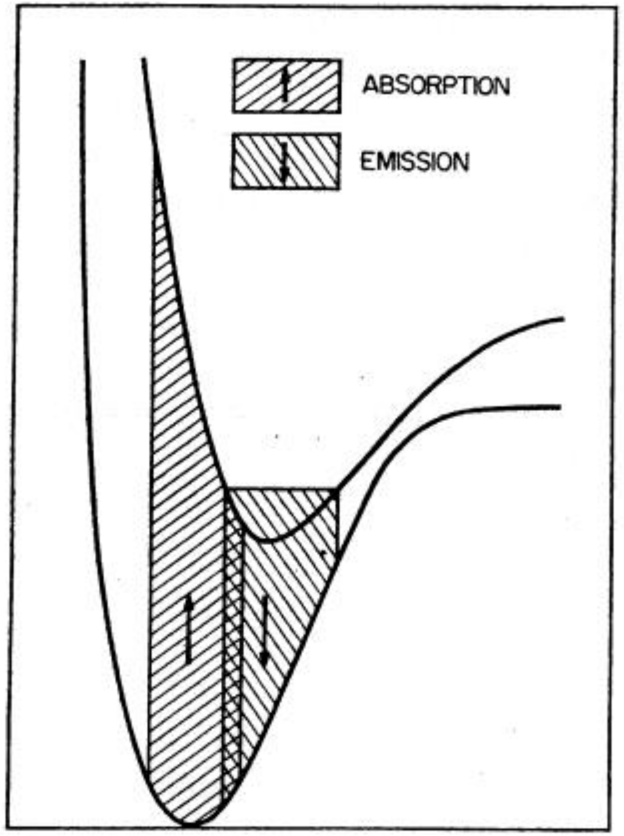
In some crystals, the proximity region F-F_1 is very close to the minimum of the excited state. These crystals are heavily quenched.

(from Birks)

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

Spectral overlap

"Luminescence properties of tungstates and molybdates phosphors: Illustration on $ALn(MO_4)_2$ compounds (A = alikaline cation, Ln = lanthanides, M = W, Mo)"
Solid State Sciences **13** (2011) 460-467



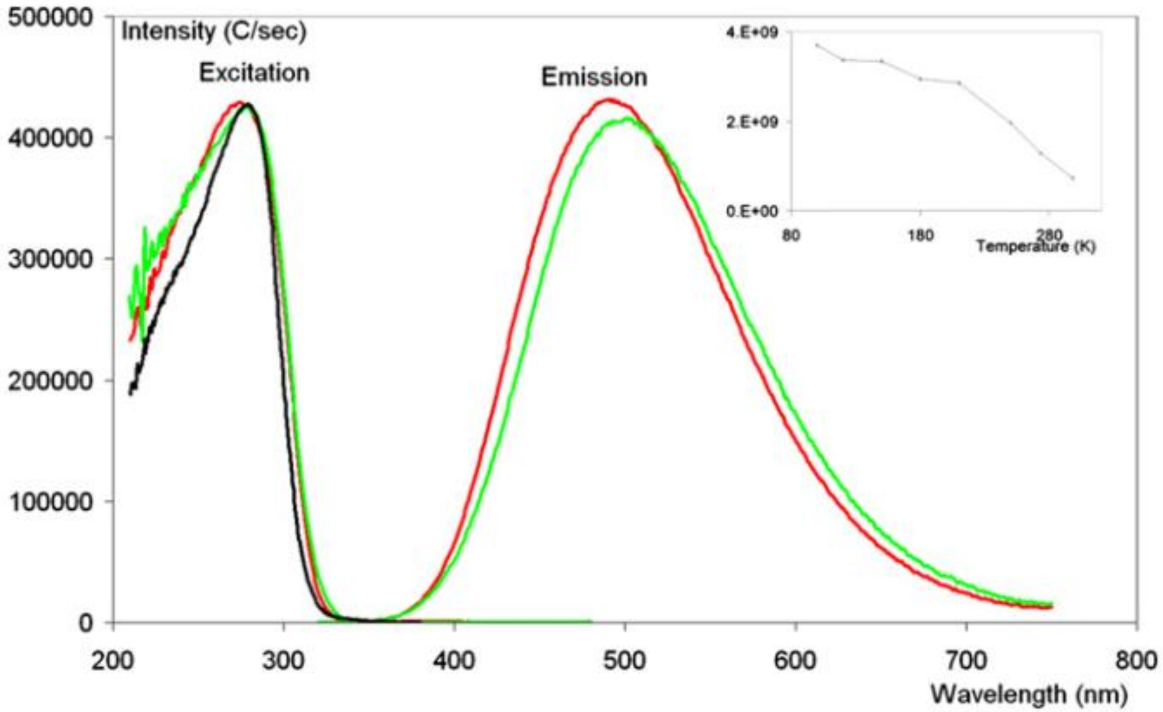
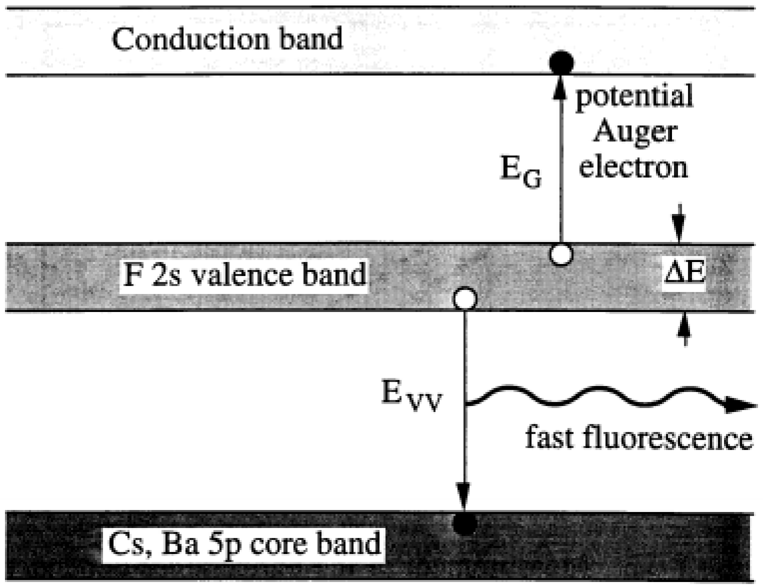


Fig. 1. Photoluminescence spectra of $LiLn(WO_4)_2$ (Ln = Lu-Red, Y-green). For excitation spectra, $\lambda_{em} = 500$ nm. For emission spectra, $\lambda_{exc} = 280$ nm. The black curve is the zero order photoluminescent excitation of $LiLu(WO_4)_2$. Inset graph represents the emission intensity (integrated area) of $LiLu(WO_4)_2$ as a function of the temperature.

Cross-luminescence (e.g. BaF_2)

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:

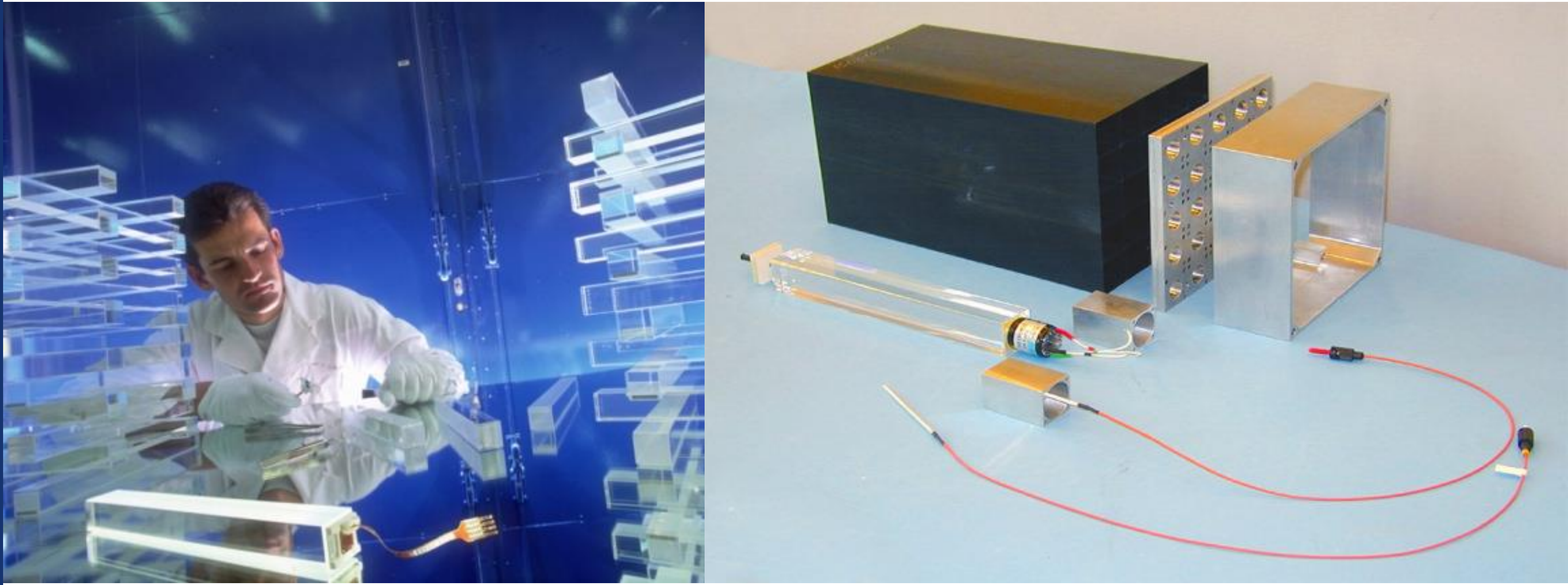
If E_{vv} is low: longer wavelength emission, longer decay time

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

Important examples

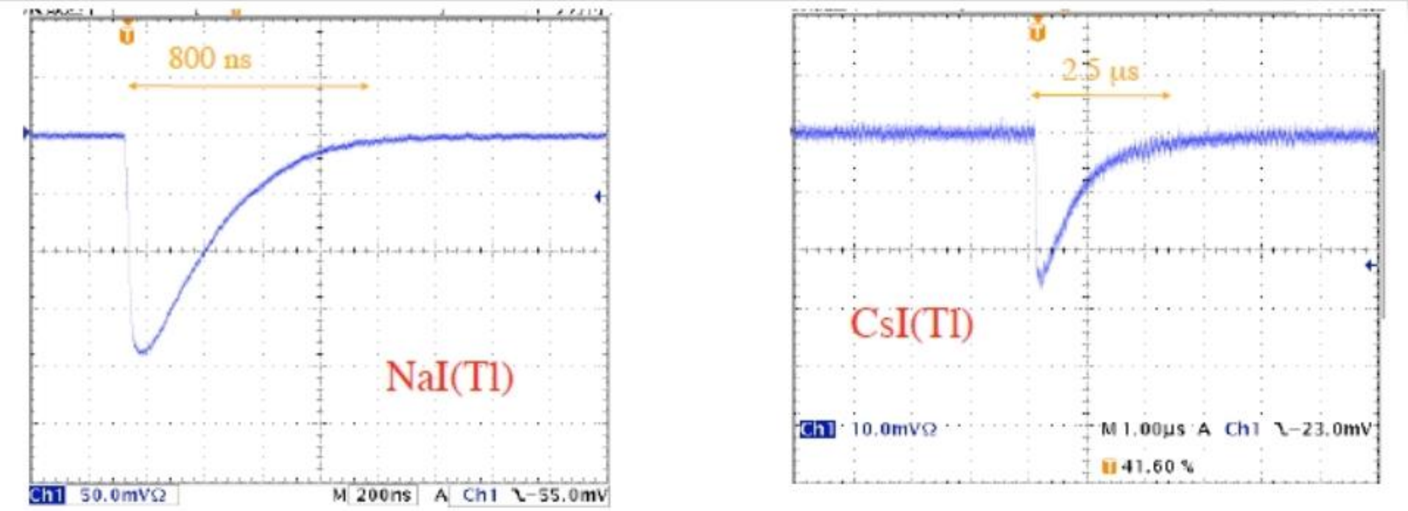
Scintillator pulse height is relative to NaI(Tl) = 100

Scintillator composition	Density (g/cm³)	Index of refraction	Wavelength of max.Em. (nm)	Decay time Constant (µs)	Scinti Pulse height[1)]
NaI(Tl)	3.67	1.9	410	0.25	100
CsI	4.51	1.8	310	0.01	6
CsI(Tl)	4.51	1.8	565	1.0	45
CaF_2(Eu)	3.19	1.4	435	0.9	50
BaF_2	4.88	1.5	190/220 310	0,0006 0.63	5 15
BGO	7.13	2.2	480	0.30	10
$CdW0_4$	7.90	2.3	540	5.0	40
$PbWO_4$	8.28	2.1	440	0.020	0.1
CeF_3	6.16	1.7	300 340	0.005 0.020	5
GSO	6.71	1.9	430	0.060	40
LSO	7	1.8	420	0.040	75
YAP	5.50	1.9	370	0.030	70

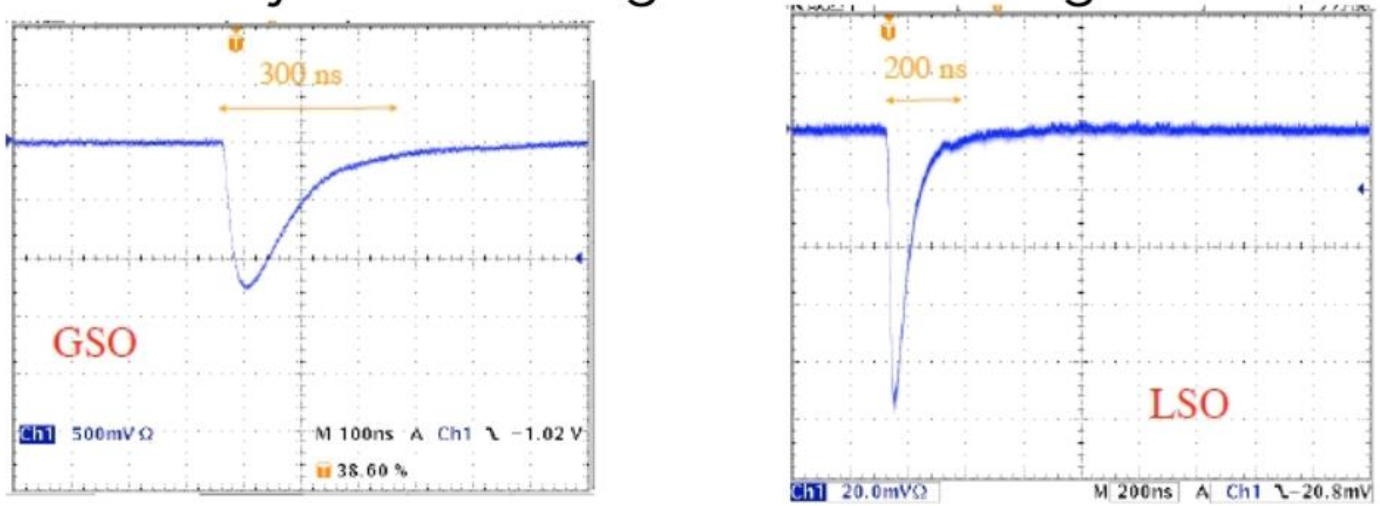


Lead tungstate ($PbWO_4$) crystals for the CMS electromagnetic calorimeter

Example signals



Different decay time among different inorganic scintillators.



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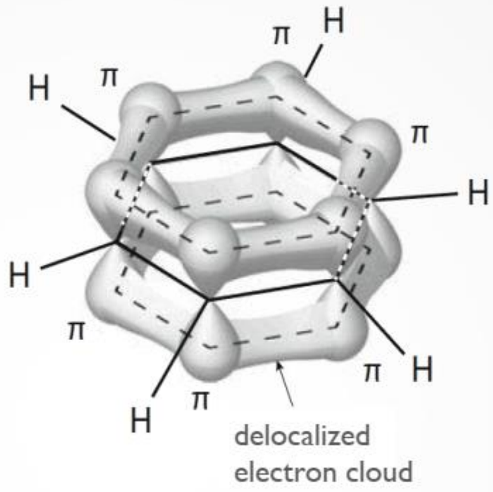
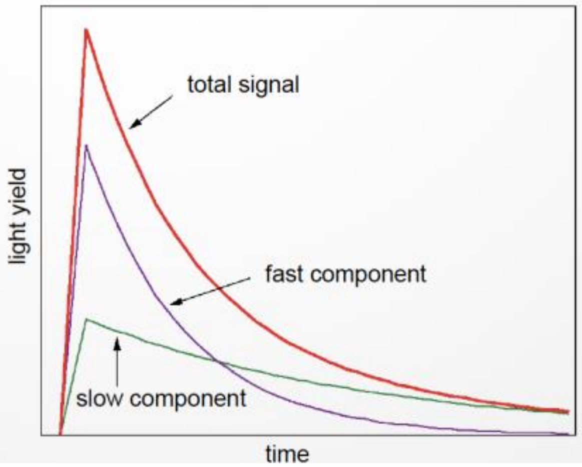
Organic scintillators

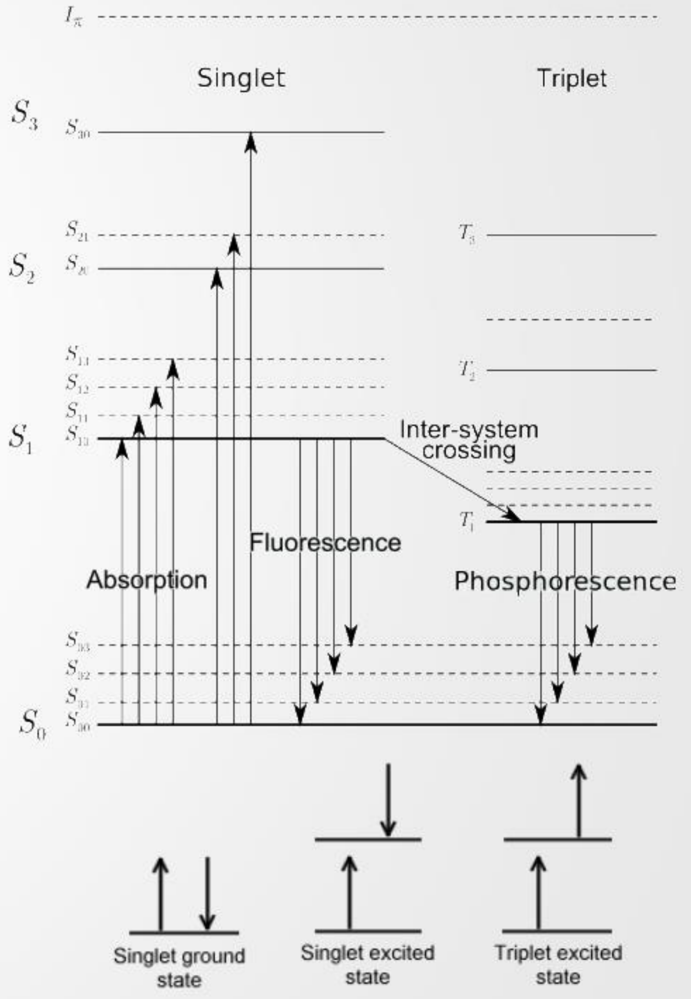
- defined by electron configuration of large carbon molecules: $\boldsymbol{\sigma}$ and π orbitals
    - Organic = carbon atoms
- Benzene* (C_6H_6):
    - p-orbital contains weakly bound π-electrons
    - fine structure from molecular vibrational and rotational modes
- Scintillation principle:
    - Excitation to $S_{1,i}$ $S_{2,i}$ $S_{3,i}$ levels
    - radiation-less drop to S_1(~ps)
    - desired O(ns) fluorescence from $S_1 \longrightarrow S_0$ ~ 3-4 eV, 400-300 nm)
    - a fraction of molecules can transit transition-less to meta-stable triplet states and cause undesired O(ms) phosphorescence.



typical scintillator signal shape



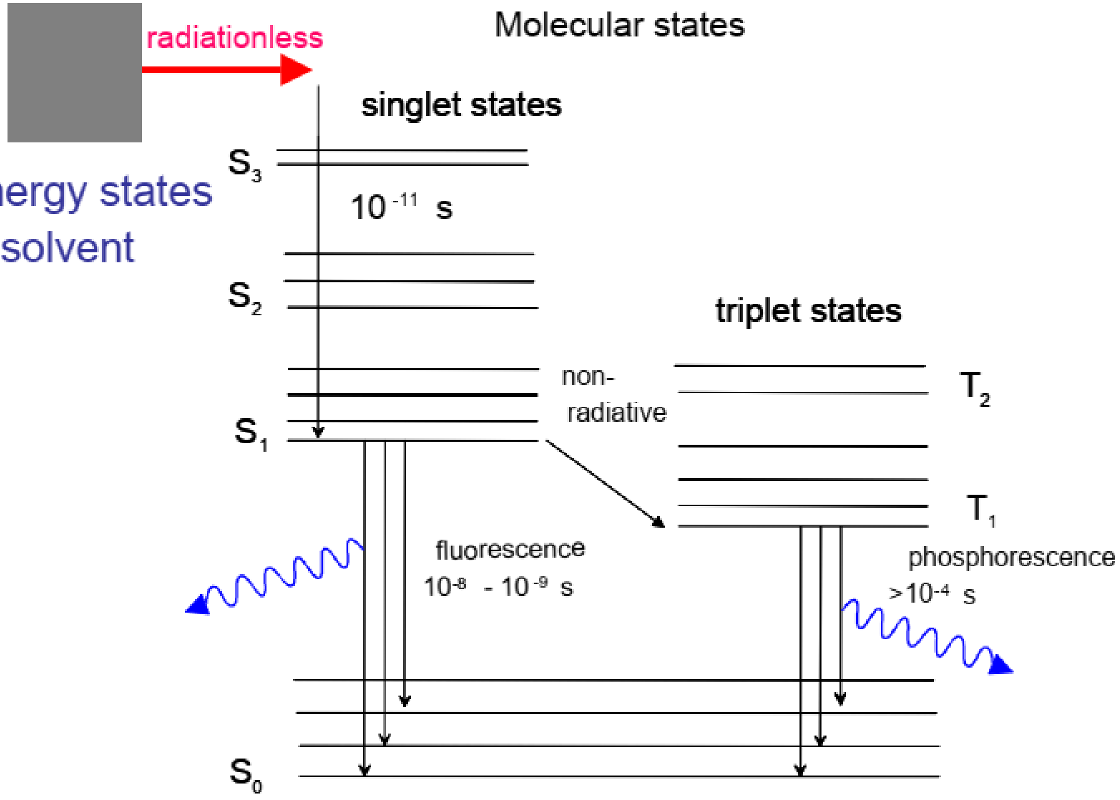
π electron states of benzene



Organic scintillators

A traversing ionizing particle releases energy in the solvent. Then, energy flows radiationless* to the scintillator. Finally, light emitted by the scintillator is absorbed (radiative transfer**) and re-emitted at longer wavelength by the secondary fluor.

Ex. energy states in the solvent



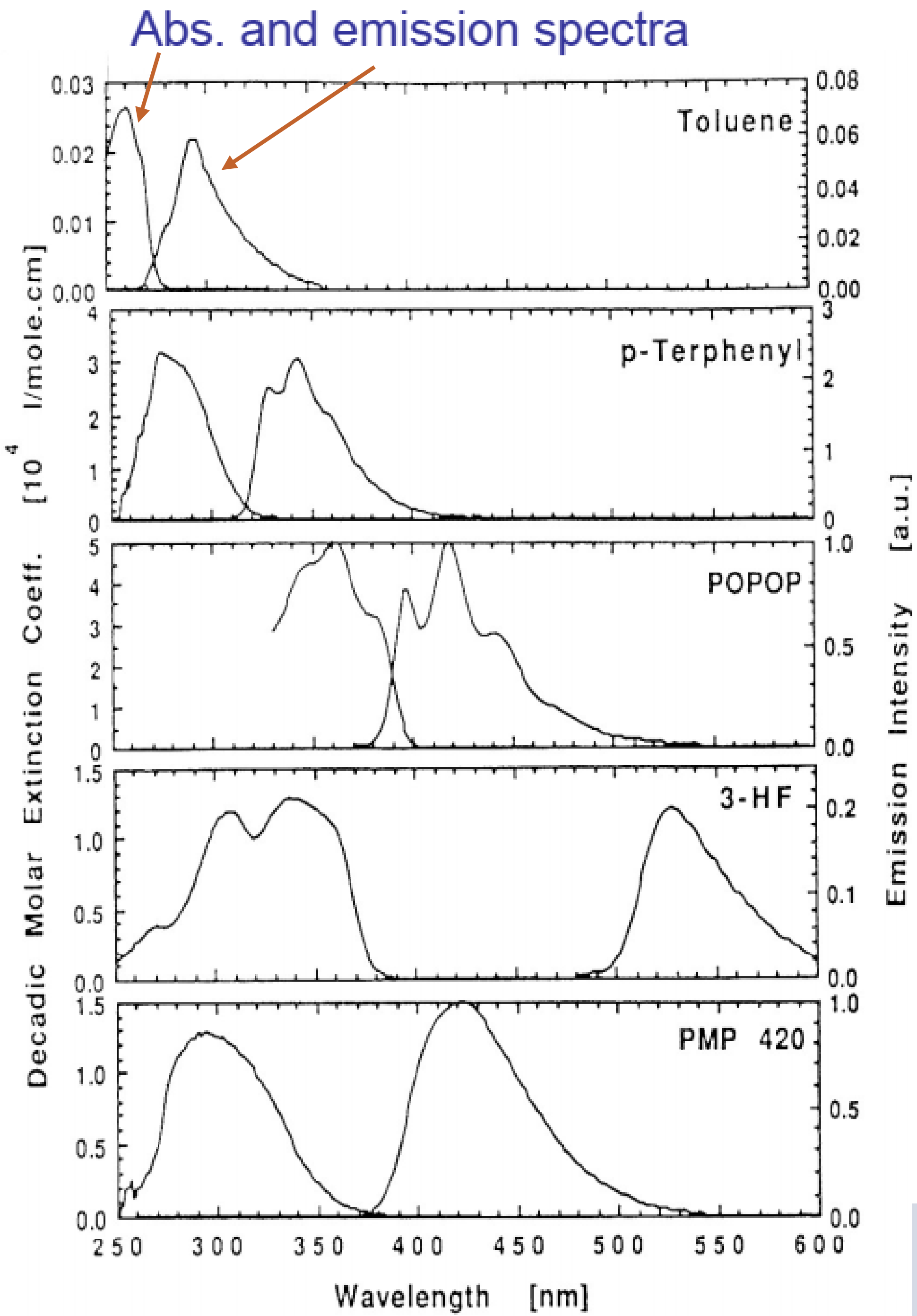
A fluor has its absorption and emission spectra shifted. The two peaks difference is called Stokes shift

*fast and local energy transfer via non-radiative dipole-dipole interactions (Förster transfer).

**~$1/R^2$ light attenuation

R is the distance between donor and acceptor

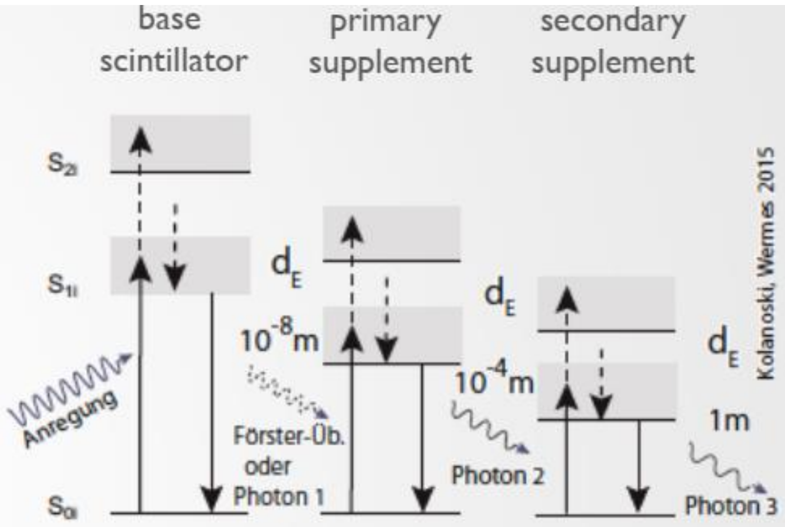
Increase efficiency using a wavelength shifter



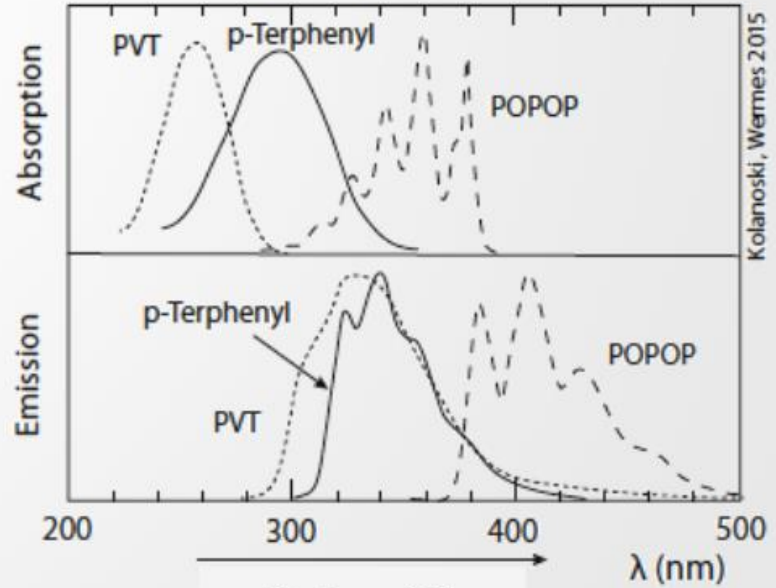
- Important liquid scintillators:
  - p-Terphenyl ($C_{18}H_{14}$), POPOP ($C_{24}H_{16}N_2O_2$), PBD ($C_{24}H_{22}N_2O$), DPO($C_{15}H_{11}NO$)
  - Mixture of one or several organic scintillators in an organic solvent (typically 3g/l solvent).
  - Average distance to molecule of a different solvent should be below the emission wavelength
- Solvents for liquid scintillators:
  - Benzol (C_6H_6), Toluol (C_7H_8), Xylol (C_8H_{10}), Phenylcyclohexan ($C_{12}H_{16}$), Triethylbenzol, Decalin ($C_{10}H_{18}$)
- Can polymerize (low efficiency scinillators Polystrol, Polyvenyltoluol, Polymethylacrylat)
- properties of these 'plastic scintillators'
  - Fast fluorescence: ca. 3–4 ns,
  - any possible detector shape
  - not very radiation resistant
- Easy use of additives
  - wave length shifter
  - increase neutron cross section
- wide range of detector applications

frequently used combinations

liquid	Benzol	p-Terphenyl	POPOP
	Toluol	DPO	BBO
	Xylol	PBD	BPO
plastic	Polyvinylbenzol (PVB)	p-Terphenyl	POPOP
	Polyvinyltoluol (PVT)	DPO	TBP
	Polystyrol (PS)	PBD	BBO/DPS



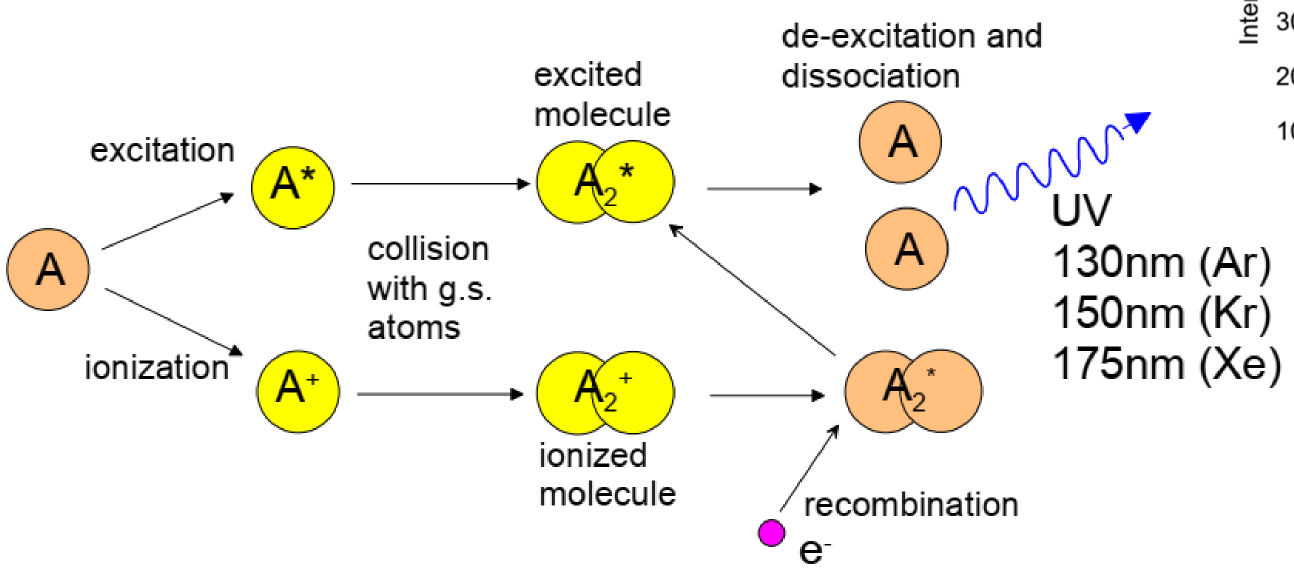
principle of wave length shift

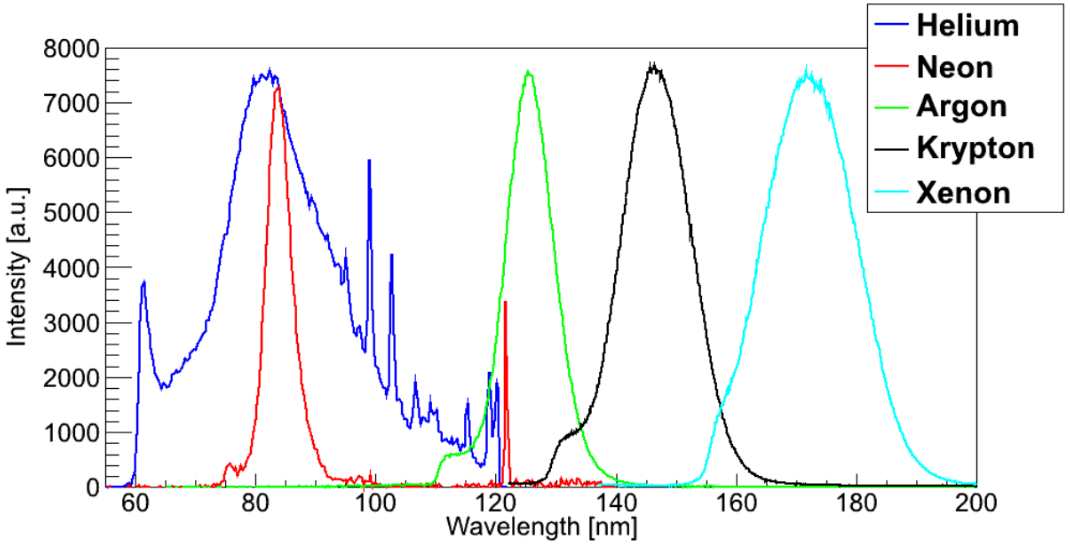


Stokes shift

Liquid noble gasses

Liquefied noble gases: LAr, LXe, LKr





Also here one finds 2 time constants: from a few ns to 1 μs.

Applications of Lar, LKr, LXe

- Liquefied noble gases well suited detector medium for rare event search
  - Efficient scintillation medium with high light yields
  - "Easily" scalable
  - Chemical purification up to a high level of purity
- Good background suppression needed

⇒ Particle discrimination on an event-by-event basis

⇒ Detailed investigation of scintillation properties wavelength- and time-resolved

TPC application

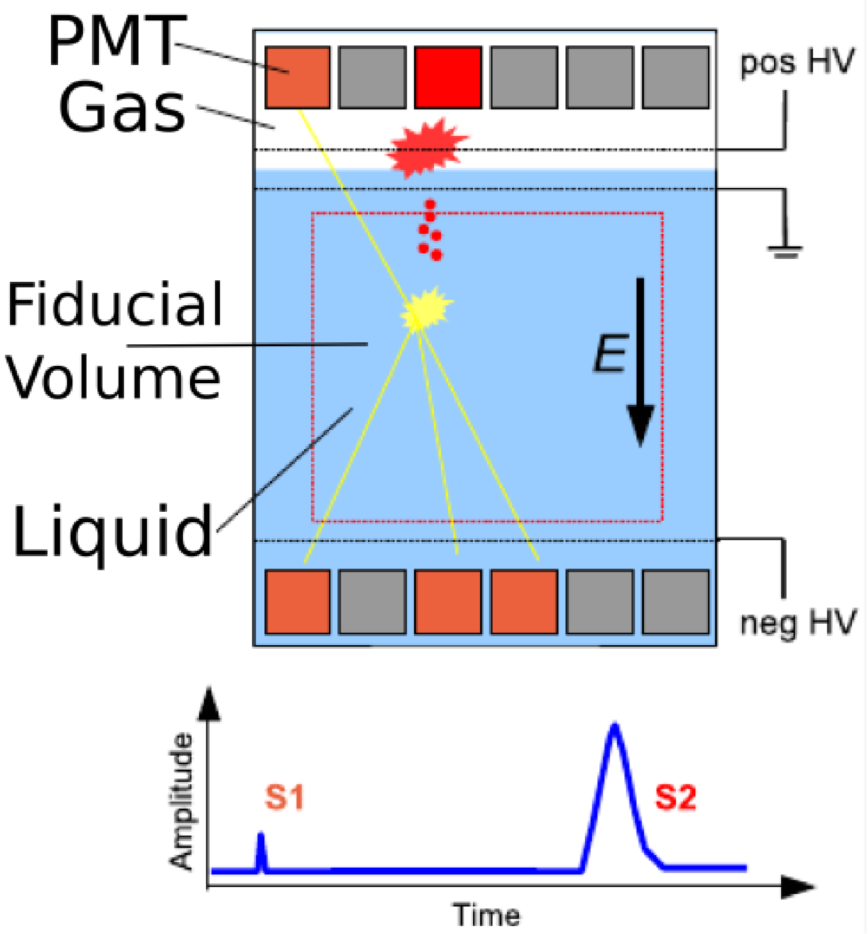


Figure: arXiv:1206.2169v1 (2012)

- Simultaneous measurement of scintillation and ionization
- 3D vertex reconstruction → z-resolution: <1 mm, xy-resolution ∼3 mm (XENON100)
- Powerful background rejection:
  - Fiducialization
  - Multi scatter-identification
  - $\frac{\text{Charge}}{\text{Light}}$ → Particle identification
  - Pulse shape discrimination (LAr detectors)
- Optical coverage and light yield smaller compared to single phase → increased threshold