A short Overview on Scintillators

By C. D’Ambrosio (CERN)

Geneva, 13 April 2005

Outline

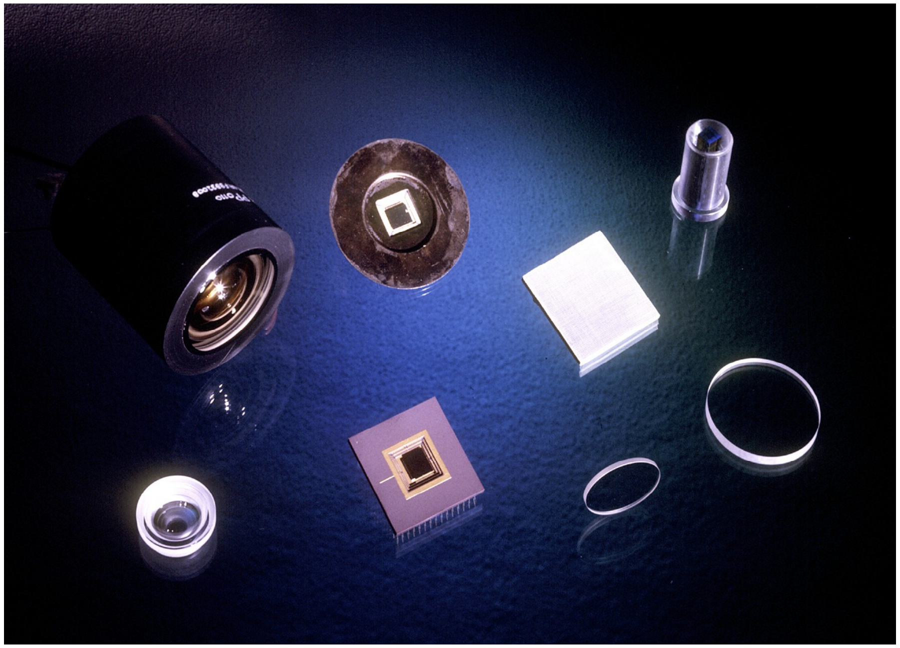
Lecture 1 - Introduction C. Joram, L. Ropelewski

Lecture 2 - Tracking Detectors L. Ropelewski, M. Moll

Lecture 3 - Scintillation and Photodetection C. D'Ambrosio, T. Gys

3a A short overview on scintillators (a personal cut)

- **What are scintillators**
- **Inorganic scintillators**
  - **Main properties**
  - **Applications**
- **Organic scintillators**
  - **Scintillation mechanisms**
  - **Plastic scintillators and their readout**
  - **Scintillating plastic fibres**

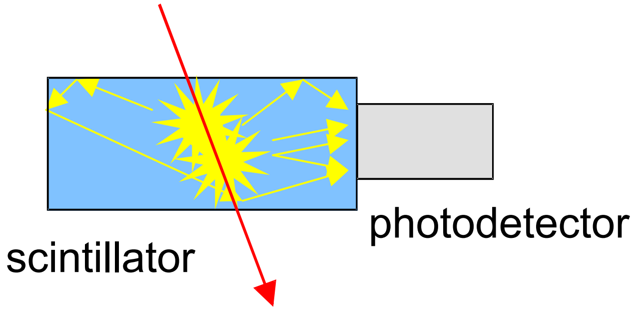


3b Photodetectors

Lecture 4 - Calorimetry, Particle ID C. Joram

Lecture 5 - Particle ID, Detector Systems C. Joram, C. D'Ambrosio

Introduction to Scintillators



Energy deposition by a ionizing particle

→generation
→transmission
→detection
} of scintillation light

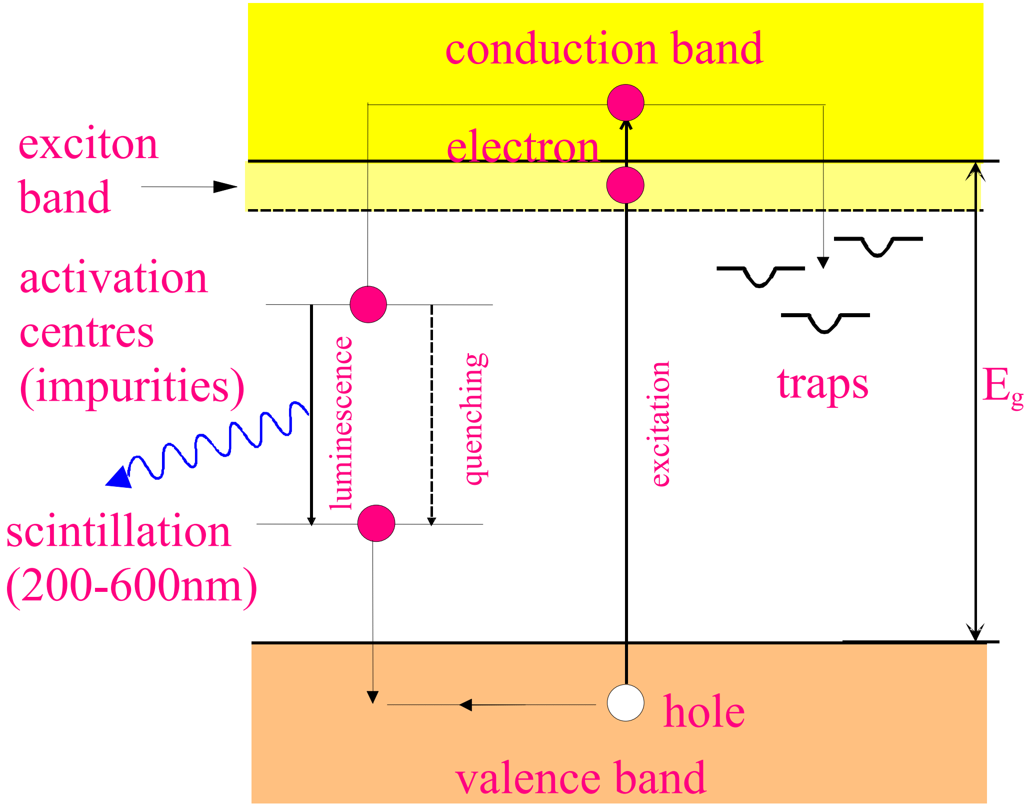
Two categories: Inorganic and organic scintillators

Inorganic (crystalline structure)	Organic (plastics or liquid solutions)
Up to 40000 photons per MeV	Up to 10000 photons per MeV
High Z	Low Z
Large variety of Z and ρ	ρ~1gr/cm^3
Undoped and doped	Doped, large choice of emission wavelength
ns to μs decay times	ns decay times
Expensive	Relatively inexpensive
E.m. calorimetry (e, γ) Medical imaging Fairly Rad. Hard (100 kGy/year)	Tracking, TOF, trigger, veto counters, sampling calorimeters. Medium Rad. Hard (10 kGy/year)

Inorganic Scintillators

- Basic scintillation mechanisms in crystals and liquefied noble gases
- Temperature dependence of scintillation yield
- Photon absorption processes in crystals
- Table of common scintillators properties
- Applications:
  - X-ray and Gamma Spectroscopy
  - Imaging

Basic crystal scintillation mechanism



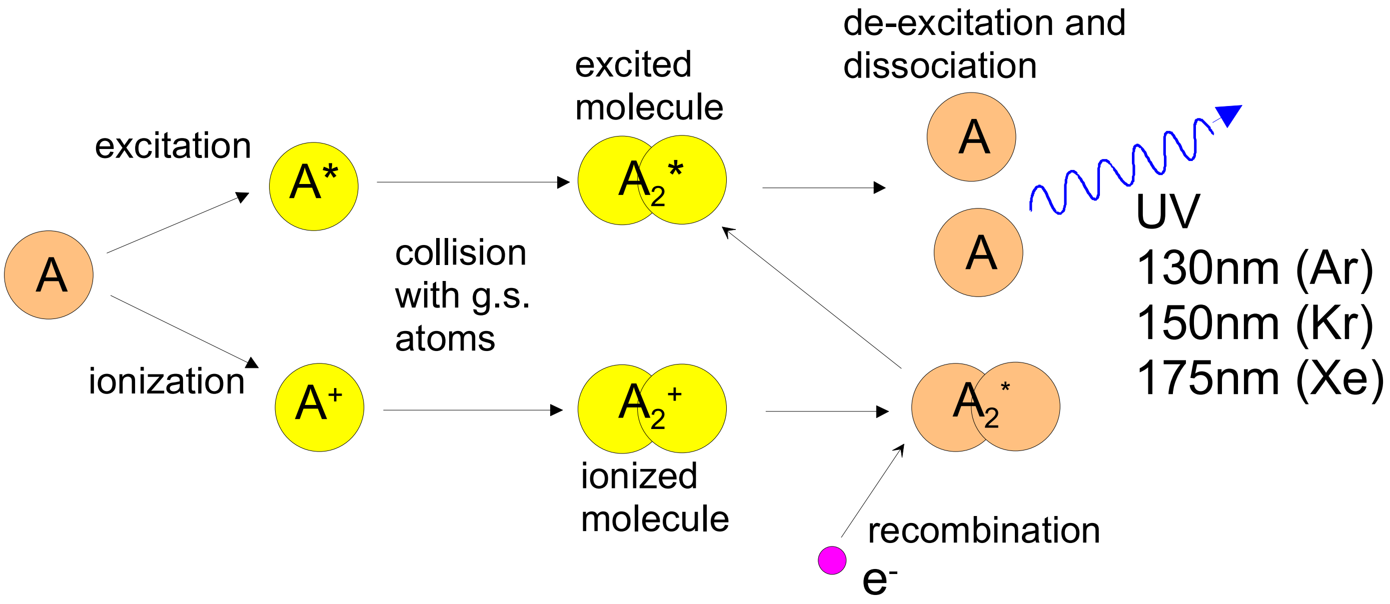
Warning, sometimes ≥ 2 time constants:

- fast recombination (ns-μs) from activation centers
- delayed recombination due to trapping (μs-ms)

•full control of growth, doping and impurities is imperative to optimize light yield, transmission and decay time

Liquefied noble gases

Liquefied noble gases: LAr, LXe, LKr



excitation

ionization

collision with g.s. atoms

excited molecule

ionized molecule

de-excitation and dissociation

recombination

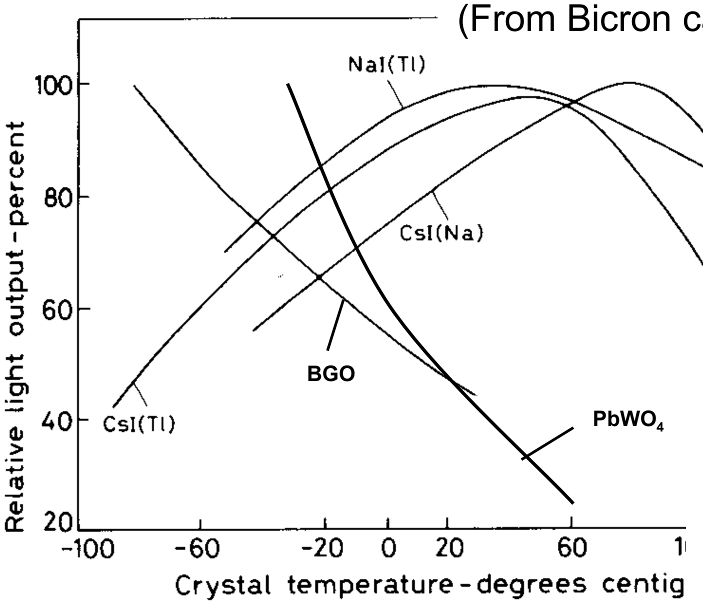
UV
130nm (Ar)
150nm (Kr)
175nm (Xe)

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

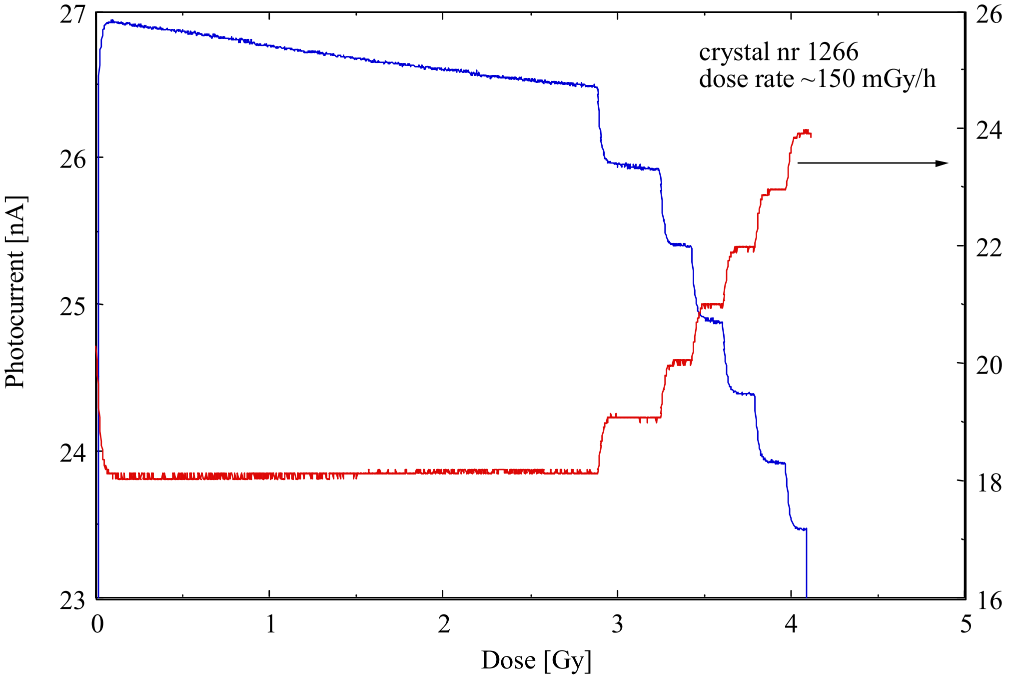
Crystals

Light output of crystals depends on temperature

(From Bicron catalogue)



Low dose irradiation of an old $PbWO_4$ crystal and check of the temperature dependence of its light yield (1996). The blue curve is the photocurrent generated by the irradiation and the red curve is the temperature of the sample.



The $PbWO_4$ crystal is used in CMS ECAL and its ~2% light yield decrease per °C asks for temp. control and monitoring

Photon absorption in crystals

The intensity I of a gamma beam traversing a target of thickness d is

$$I = I_0 e^{-\mu d}$$

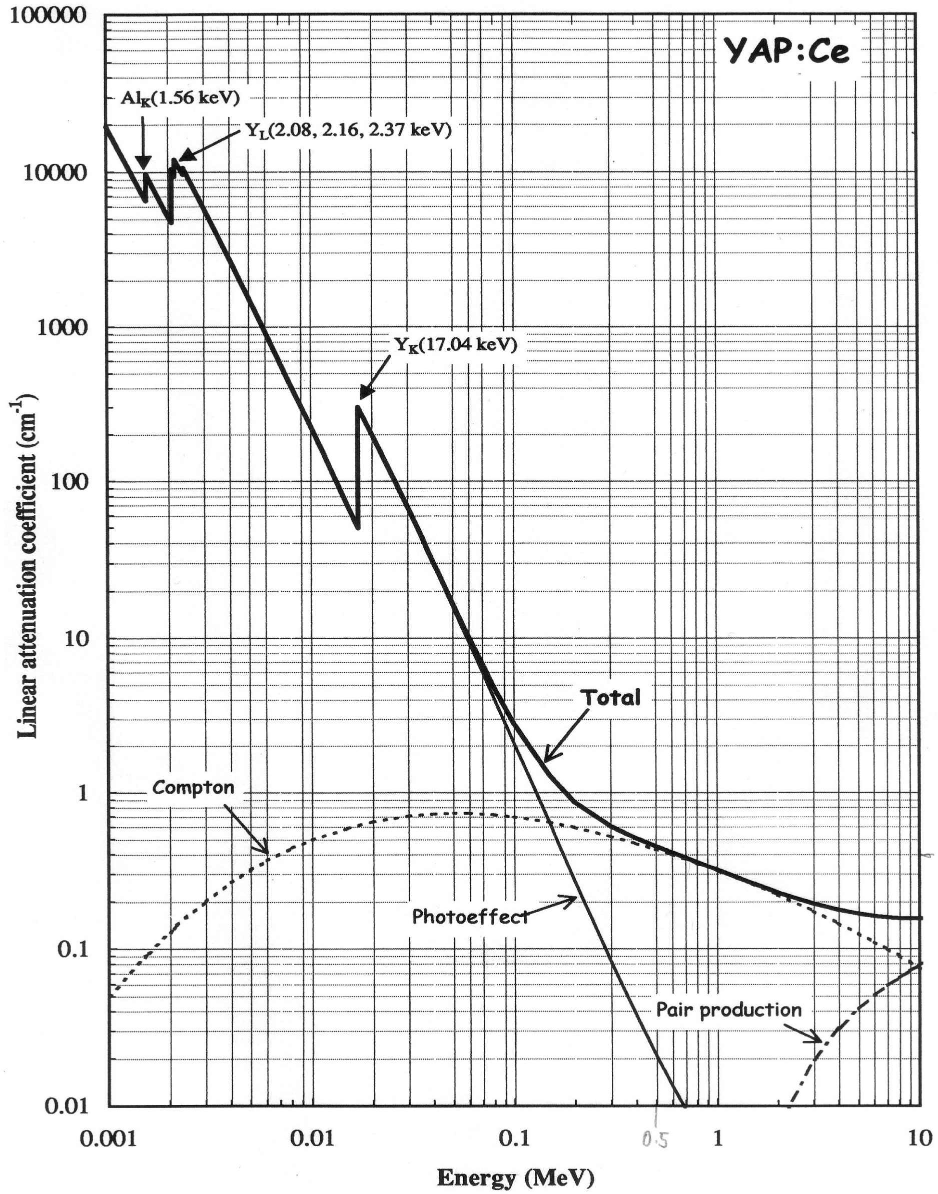
Where μ is the sum of three processes taking place in the material:

Photoel. Abs. $\rightarrow Z^4$ to $Z^5 \rightarrow E^{-3.5}$ to E^{-1}

Compton scatt. $\rightarrow Z$ $\rightarrow E^{-1}$

Pair production $\rightarrow Z^2$ $\rightarrow \ln E$

(curve will extend to higher energies, see Christian's talk)



CERN Academic Training Programme 2004/2005

Properties of some crystal scintillators

Scintillator composition	Density (g/cm^3)	Index of refraction	Wavelength of max.Em. (nm)	Decay time Constant (μs)	Scinti Pulse height$^{1)}$	Notes
NaI(Tl)	3.67	1.9	410	0.25	100	2)
CsI	4.51	1.8	310	0.01	6	3)
CsI(Tl)	4.51	1.8	565	1.0	45	3)
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	

1) Relative to NaI(Tl) in %; 2) Hygroscopic; 3) Water soluble

Most common applications of inorganic scintillators

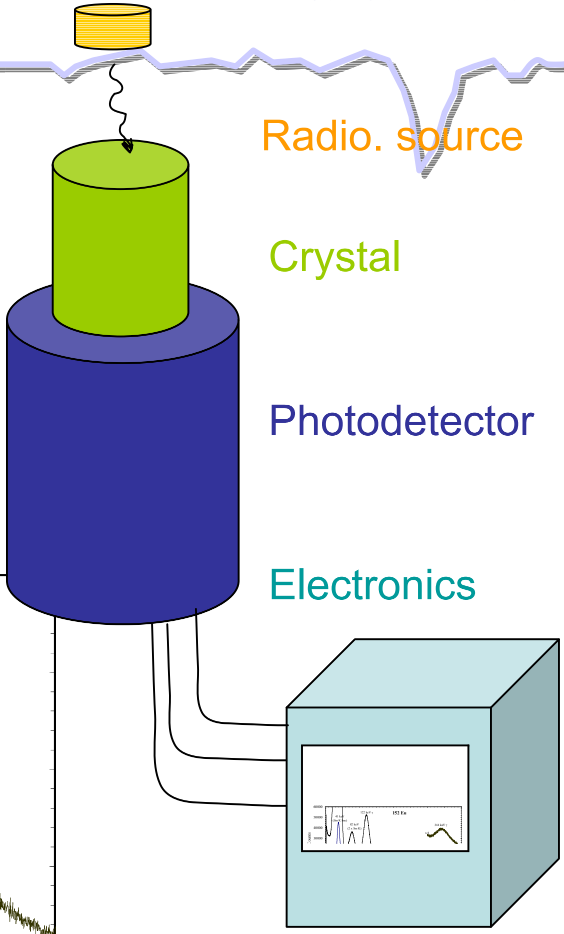
- Calorimetry (for HEP, see Christian's lecture)
- X-ray and gamma spectroscopy
- Imaging
  - Positron Emission Tomography (PET) in medical imaging
  - Gamma Imaging (Anger camera) (see Thierry's talk)
- Monitoring in nuclear plants
- Oil wells, Mining, etc.

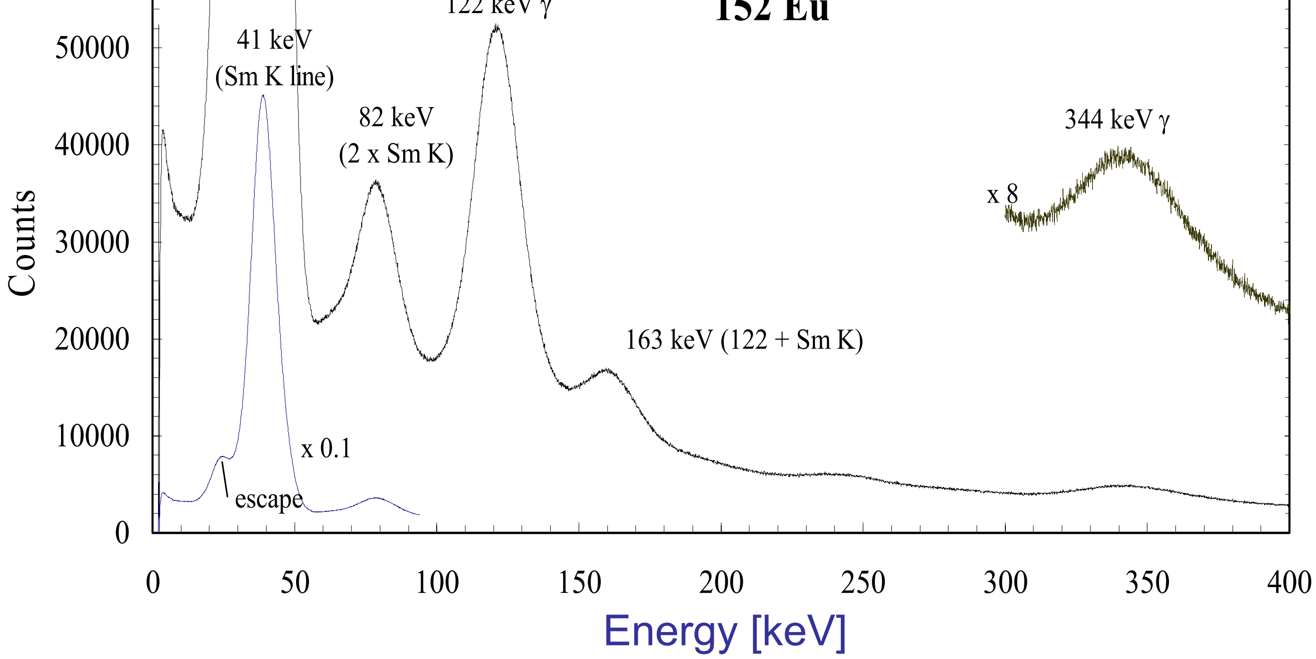
X-ray and gamma spectroscopy

The simple set-up:

each detected gamma provides an amplitude signal, which fills a pulse-height spectrum.

We can monitor radiation, study atomic or nuclear spectra, research and characterize new crystals, test new photo-detectors, produce special probes, etc..





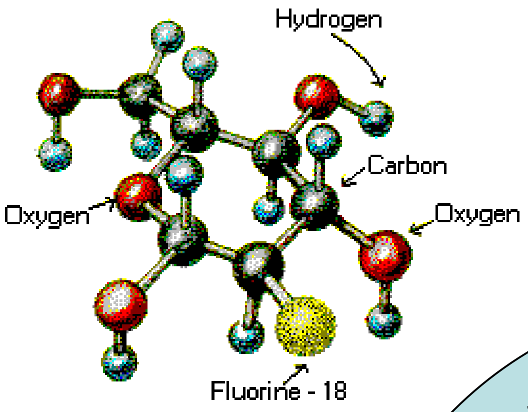
Irradiation of a YAP(Ce) crystal by ^{152}Eu on a HPD

Positron Emission Tomography (PET)

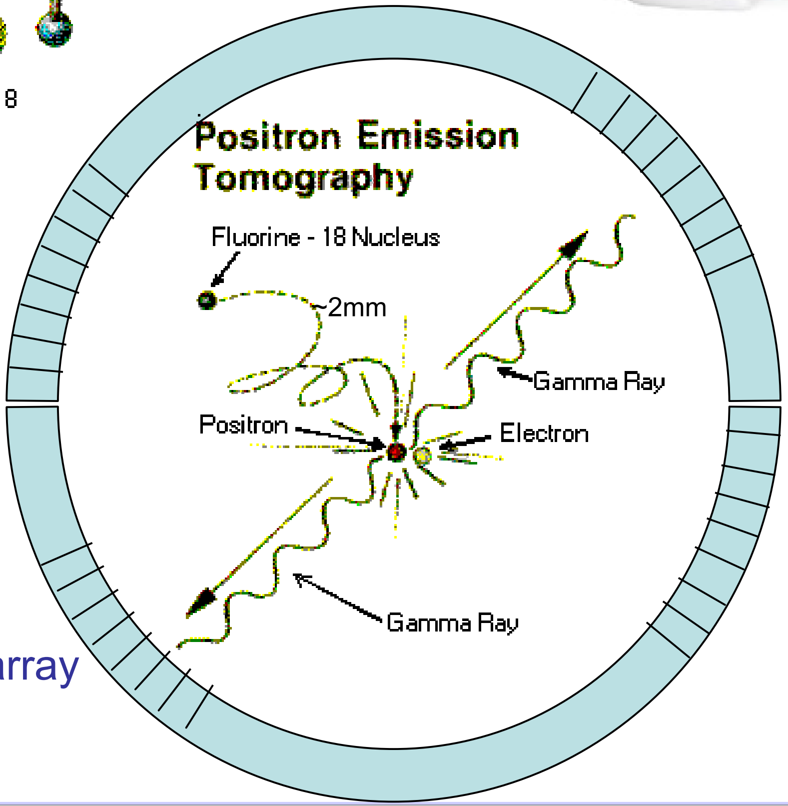
http://www.medical.philips.com/main/products/pet/products/gemini/clinicalimages/10/index.asp

http://www.triumf.ca/welcome/petscan.html

2-fluoro-
2-deoxy-D-glucose
"FDG"



NOT TO SCALE!!



Crystals array

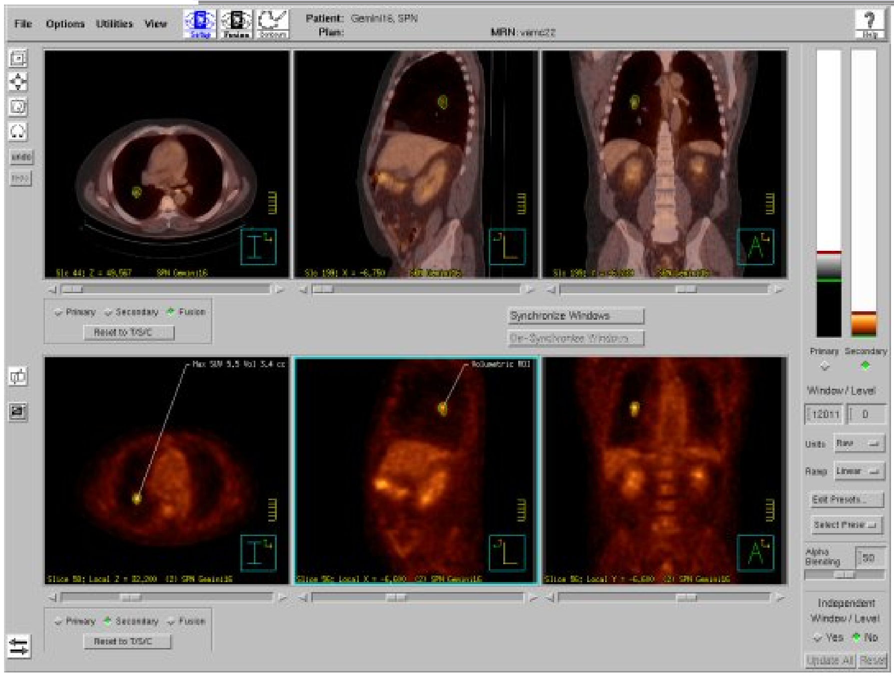
2 x 511 keV energy

γ-γ co-linearity

time coincidence

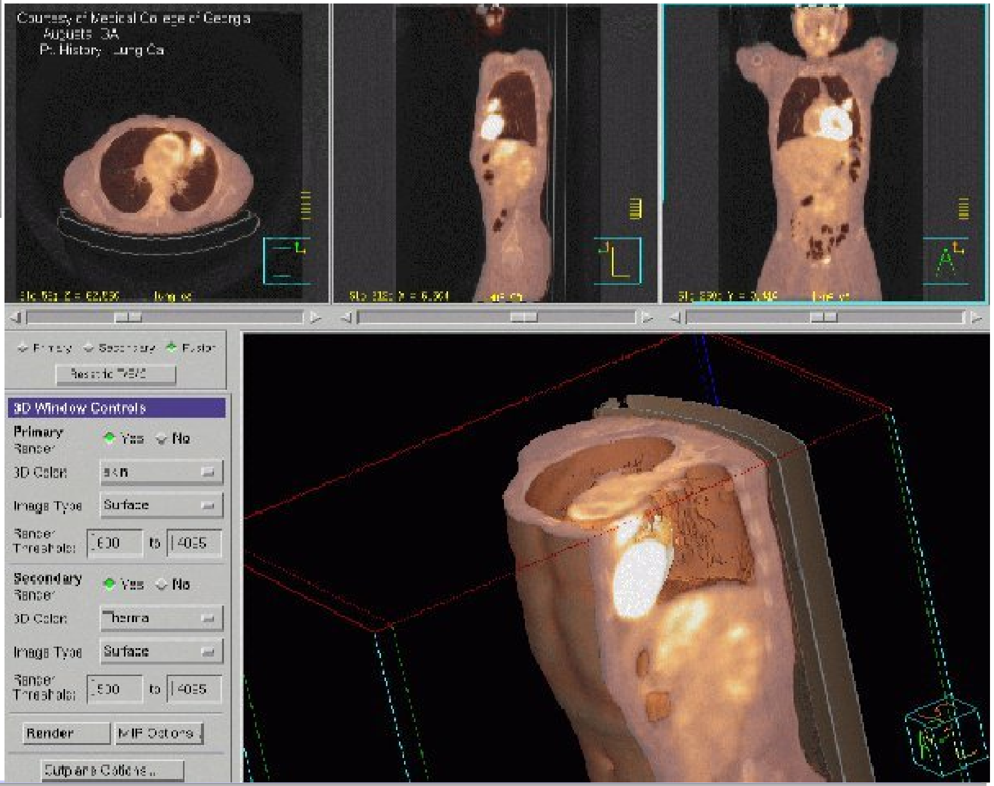
reconstruct functional image

PET images to be found on the web



Patient: Gemini16, SPN
Plan:
MRN: vamc22

http://www.medical.philips.com/main/products/pet/products/gemini/clinicalimages



Courtesy of Medical College of Georgia
Augusta GA
Pt. History: Lung Ca

3D Window Controls
Primary Render: ● Yes ○ No
3D Color: Skin
Image Type: Surface
Render Thresholds: 600 to 4095
Secondary Render: ● Yes ○ No
3D Color: Thermal
Image Type: Surface
Render Thresholds: 500 to 4095

Main R&D on inorganic scintillators

- Higher densities for higher Z (improve photoabsorption)
- High light yield (NaI(Tl) light yield still unchallenged)
- Short decay time (improve time resolution)
- Improve light coupling with photon detector
- More radiation hard
- Inexpensive, “easy” to manufacture, reproducible
- Large size, easy handling and “machinable”

Organic Scintillators

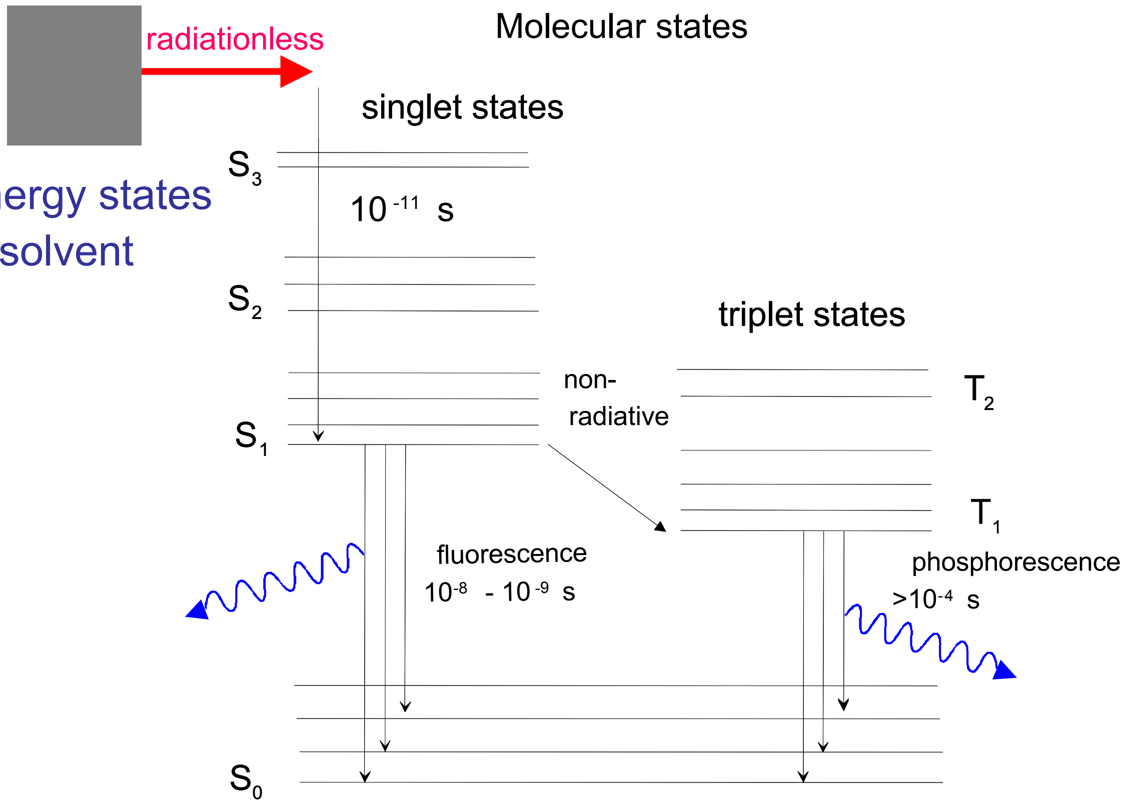
- Basic scintillation mechanisms in organic scintillators
- Förster energy transfer and self absorption
- One dopant and two dopants scintillators
- Readout of scintillators
- Applications of organic scintillators
- Example: small diameter scintillating fibres and their readout

Liquid and plastic scintillators

They usually consist of a solvent + scintillator and a secondary fluor as wavelength shifters.

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).

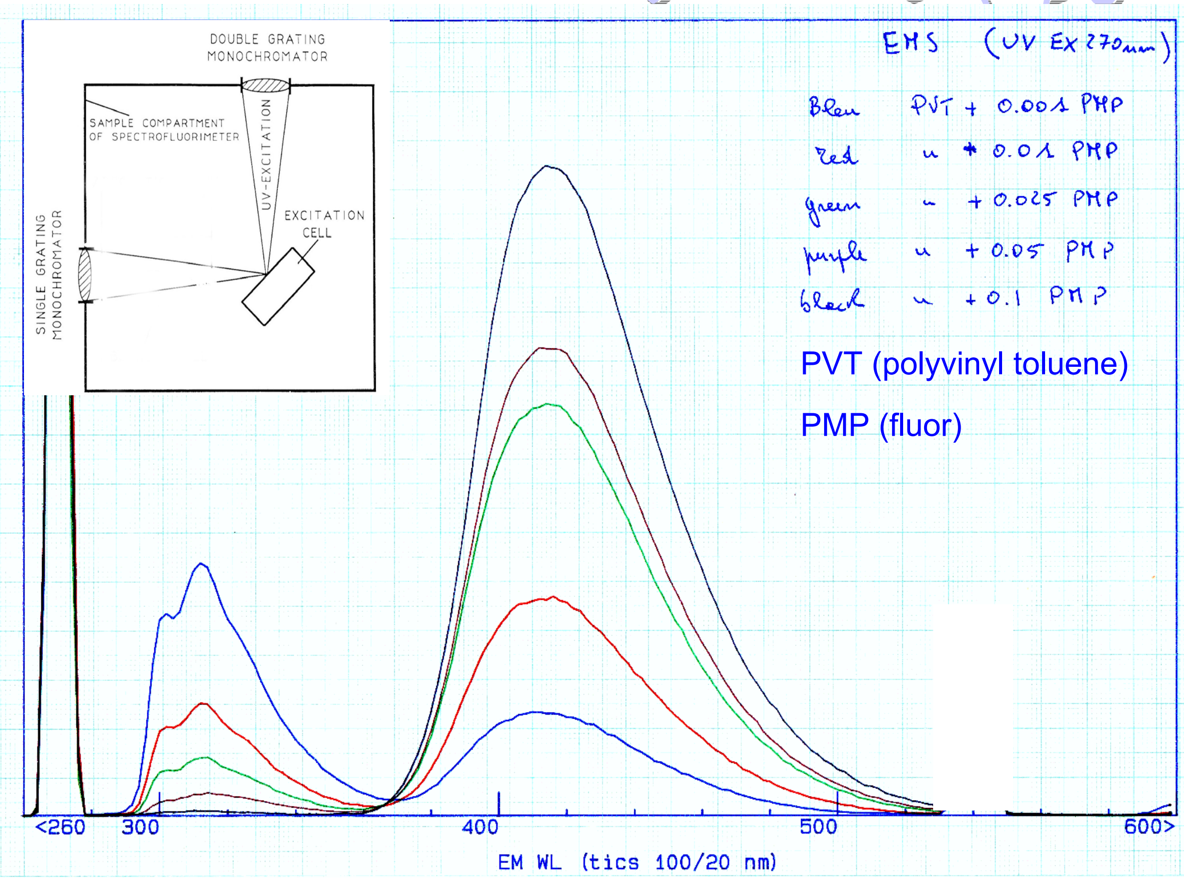
**~$1/R^2$ light attenuation

The Förster transfer

Efficient Förster transfer asks for high concentrations of scintillator:

$$k_{D\to A} \propto \frac{1}{\tau_D R_{DA}^6} \int \frac{f_D(\nu)\varepsilon_A(\nu)}{\nu^4} d\nu$$

where the integral is the overlap between Acceptor abs. and Donor emission spectra and R is the D-A distance



PVT (polyvinyl toluene)

PMP (fluor)

But…

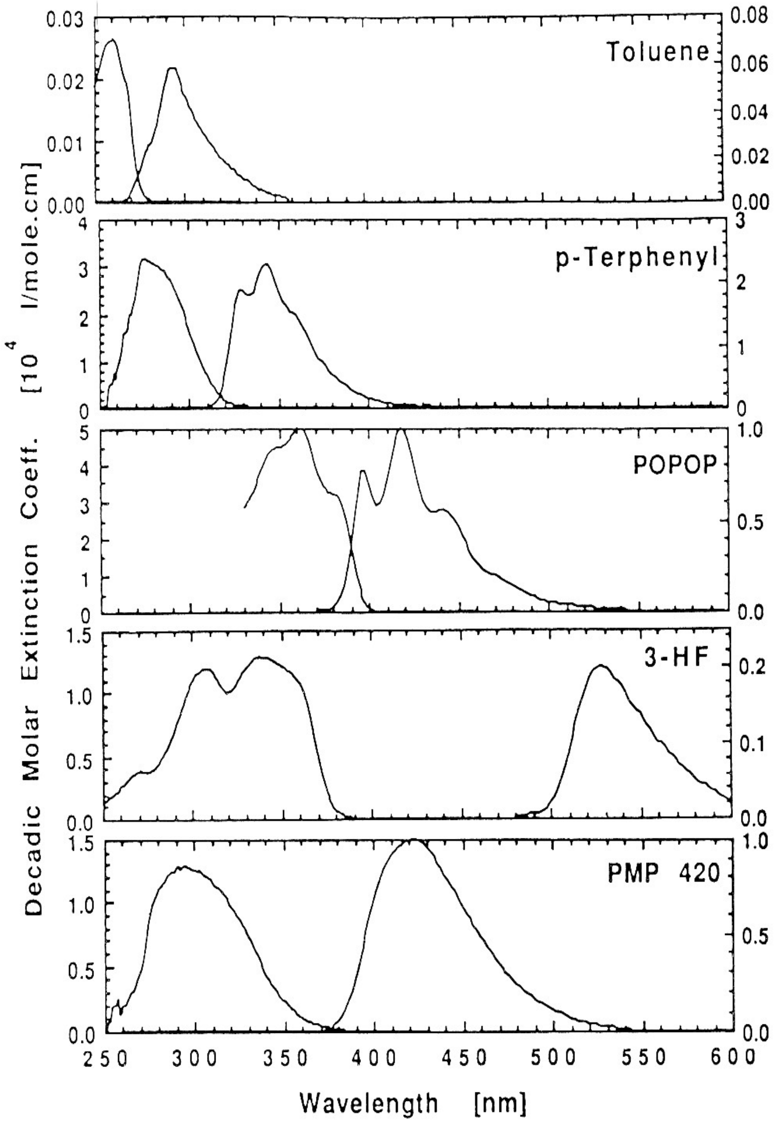
Self-absorption increases with doping concentration, that is smaller light yields and shorter attenuation lengths:

Therefore, add a low concentration wavelenght shifter (2 dop. Scheme) **or**

Find large Stokes shift dopants (1 dop. Scheme, ex. 3hf, pmp)

Two / One Dopant scheme

Abs. and emission spectra

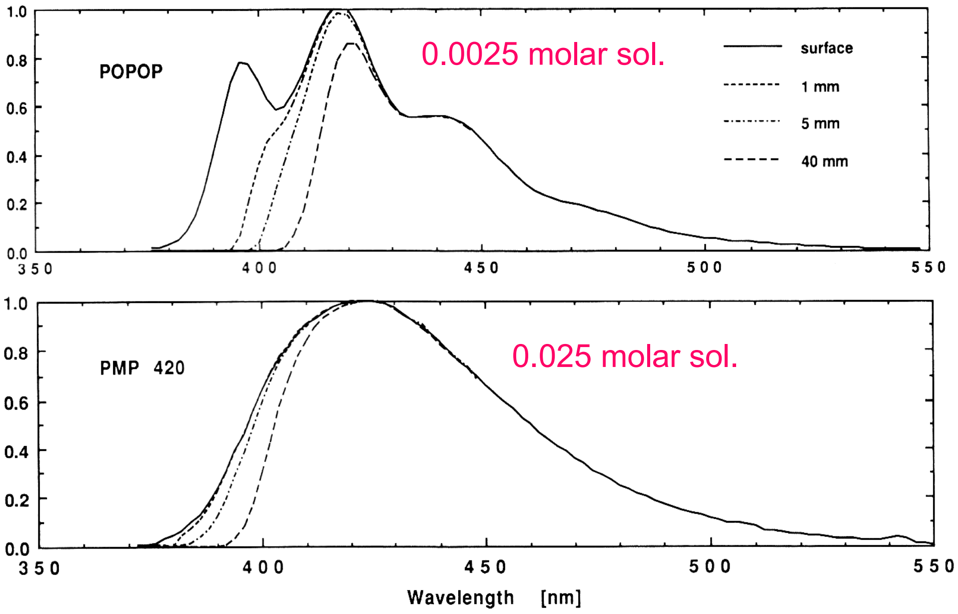


solvent + scintillator + wave shifter

Förster Radiative

Förster

solvent + large stokes shift scintillator



0.0025 molar sol.

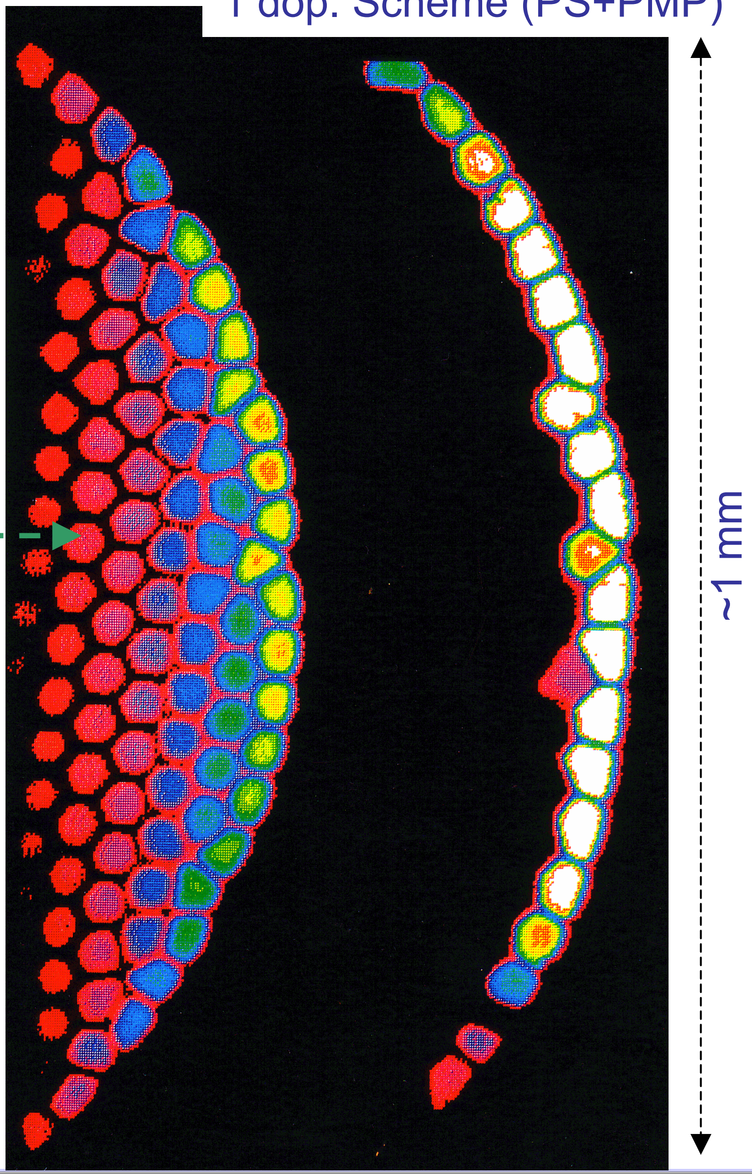
0.025 molar sol.

Dopants in toluene: large Stokes shift dopants feature a much smaller self-absorption

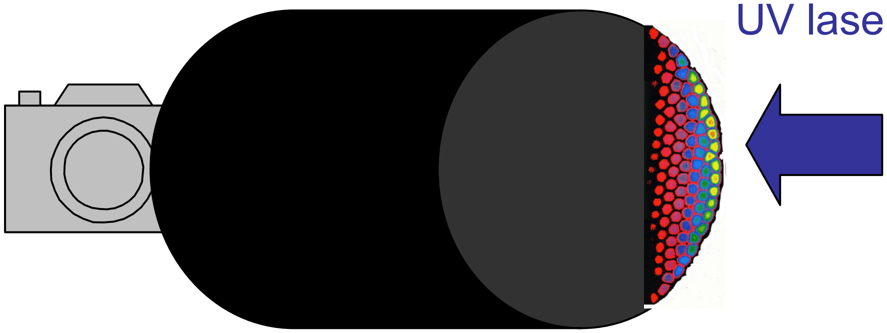
Application of the two types of doping

The two dopants scheme is the most common: it is applied to all plastic scintillators, down to ~1mm fibres.

The one dopant scheme is needed to keep the light emission local (only Förster transfer) as it is the case for small diameter fibres



2 dop. Scheme (PS+p-Ter+POPOP)



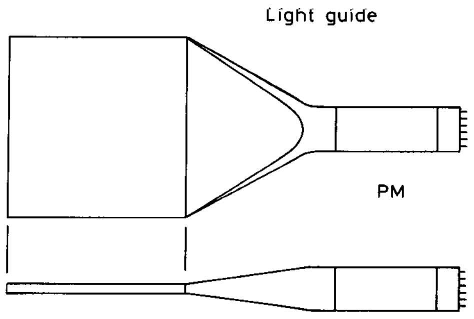
Plastic microfibres bundle
(30 µm dia.)

Scintillators readout

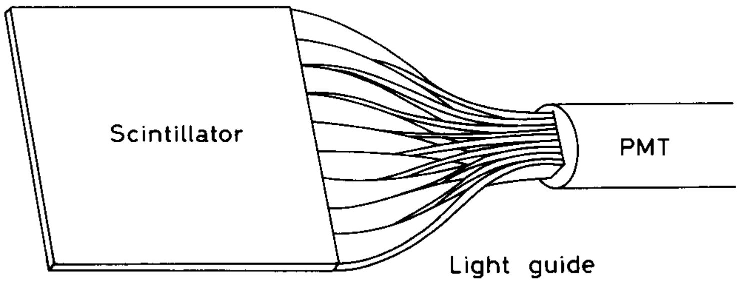
Readout has to be adapted to geometry, granularity and emission spectrum of scintillator.

Geometrical adaptation:

- Light guides: transfer by total internal reflection (+outer reflector)

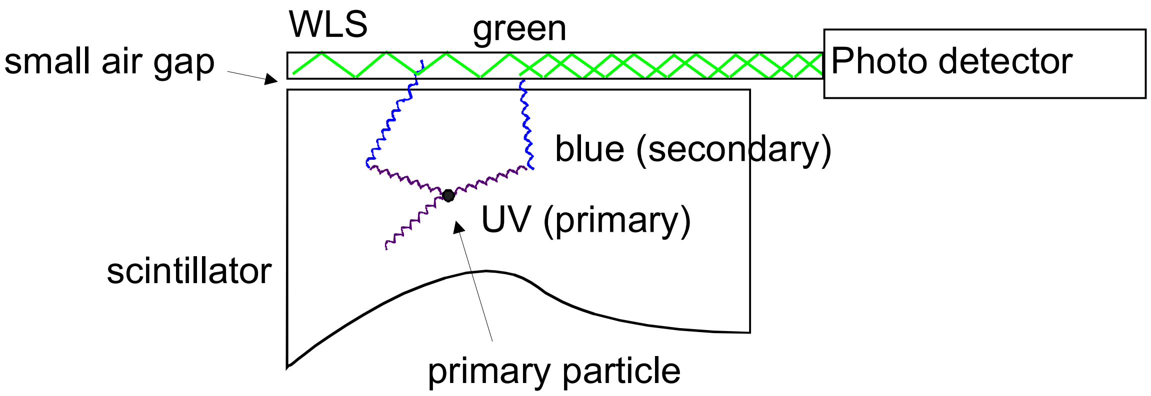


"fish tail"



adiabatic

- wavelength shifter (WLS) bars



WLS

green

Photo detector

small air gap

blue (secondary)

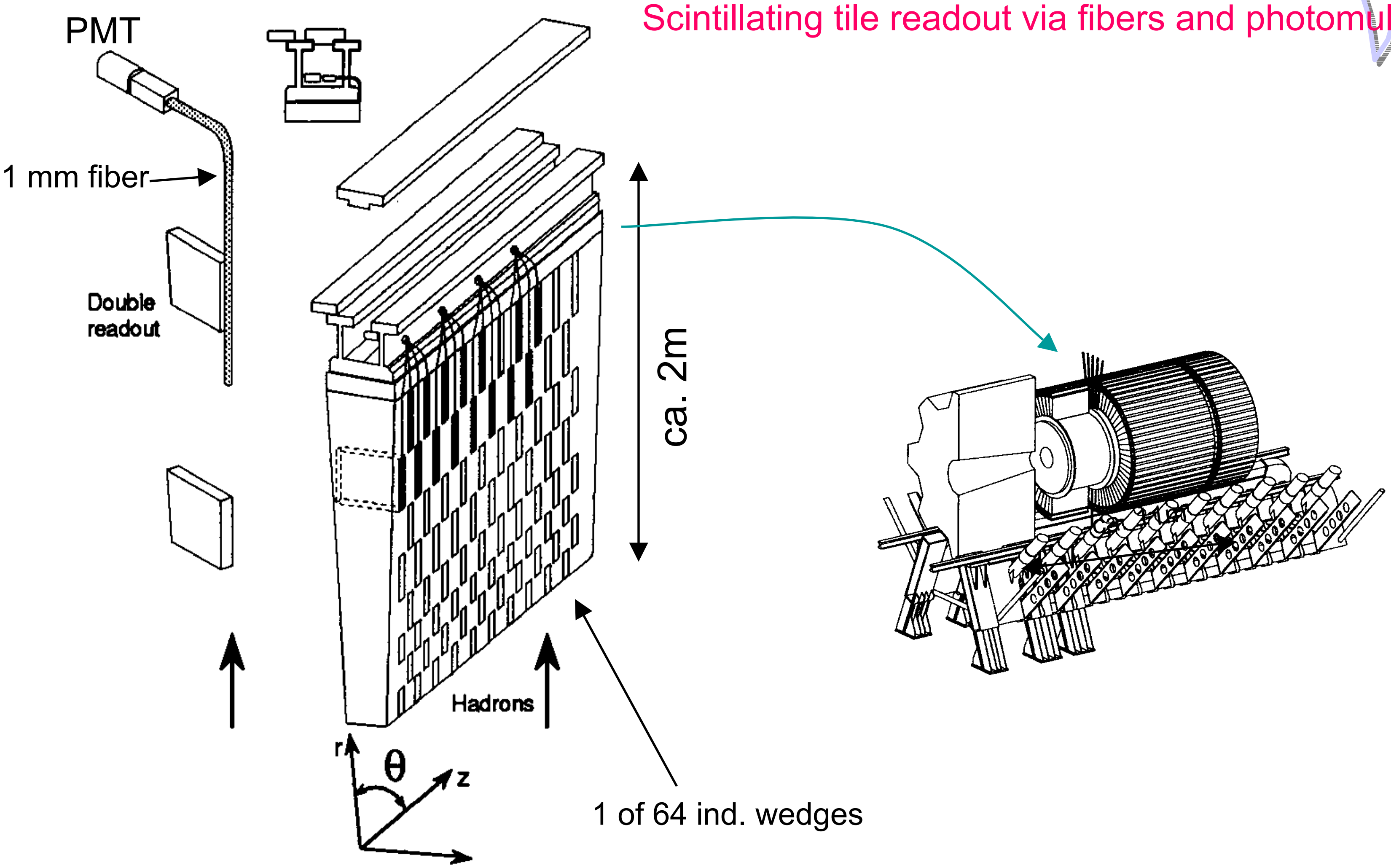
UV (primary)

scintillator

primary particle

ATLAS Hadron Calorimeter

Scintillating tile readout via fibers and photomultipliers



Periodical arrangement of scintillator tiles (3 mm thick) in a steel absorber structure

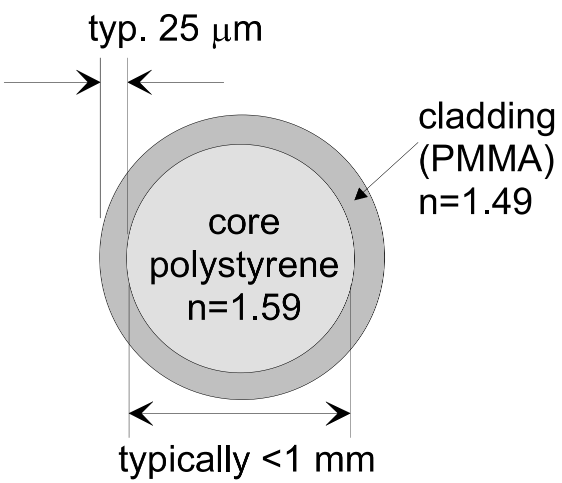
(ATLAS TDR)

Most common applications of organic scintillators

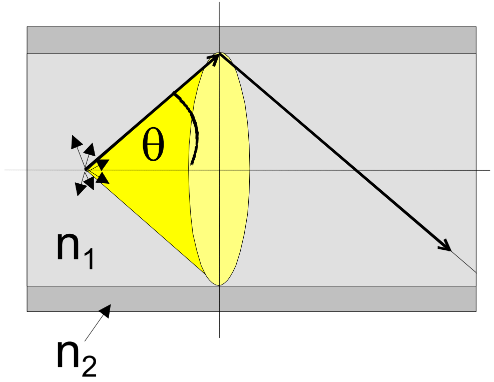
Large volume liquid or solid detectors (in form of tiles): underground experiments, sampling calorimeters (HCAL in CMS or ATLAS, etc.), counters, light guides.

High precision, small volume active targets and fibre tracking (UA2, D0, CHORUS).

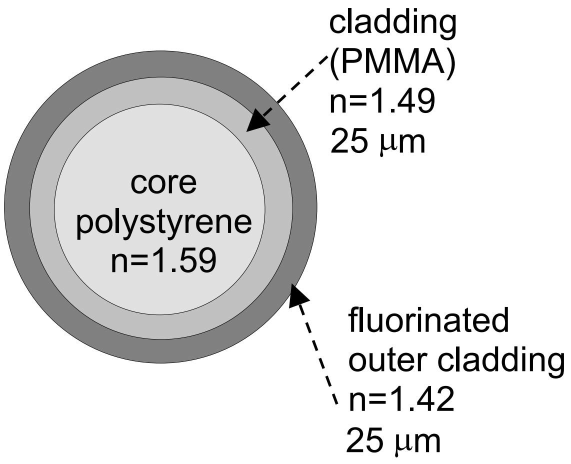
As an example, a scintillating plastic fibre working principle:



light transport by total internal reflection



Double cladding system
(developed by RD7)



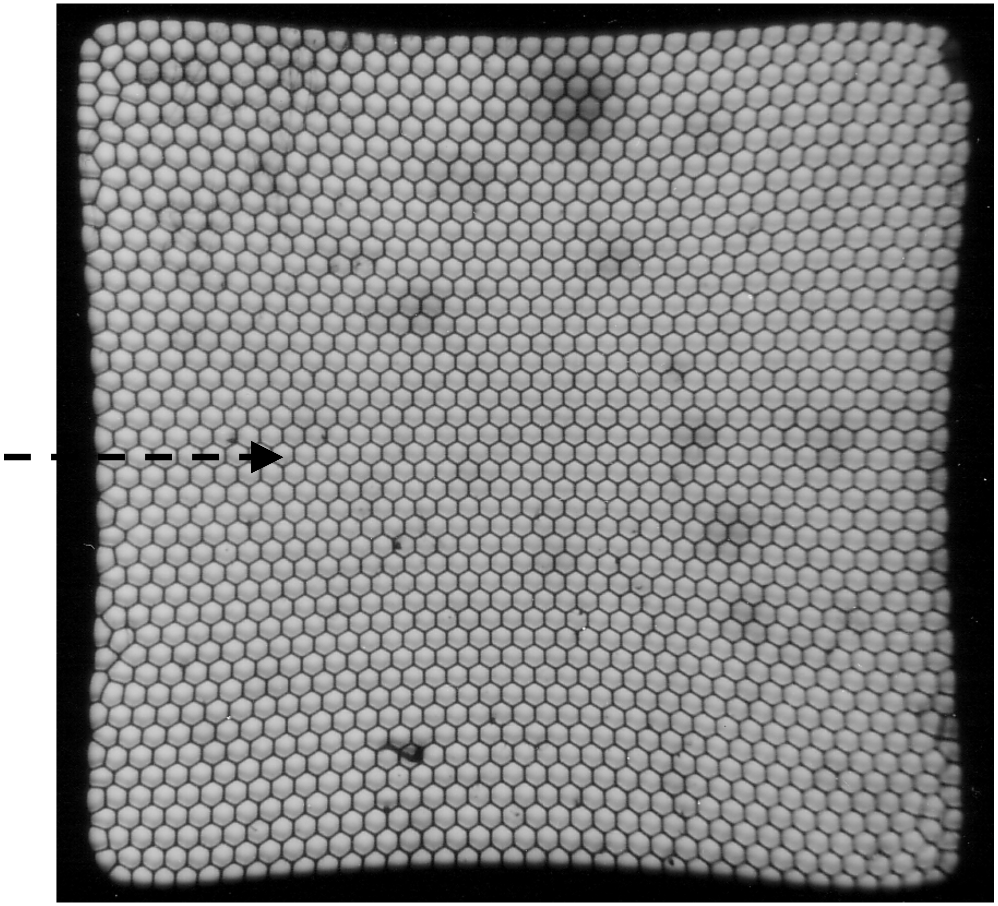
$$\frac{d\Omega}{4\pi} = 0.5\,(1-\cos^2\theta) = 3\%$$

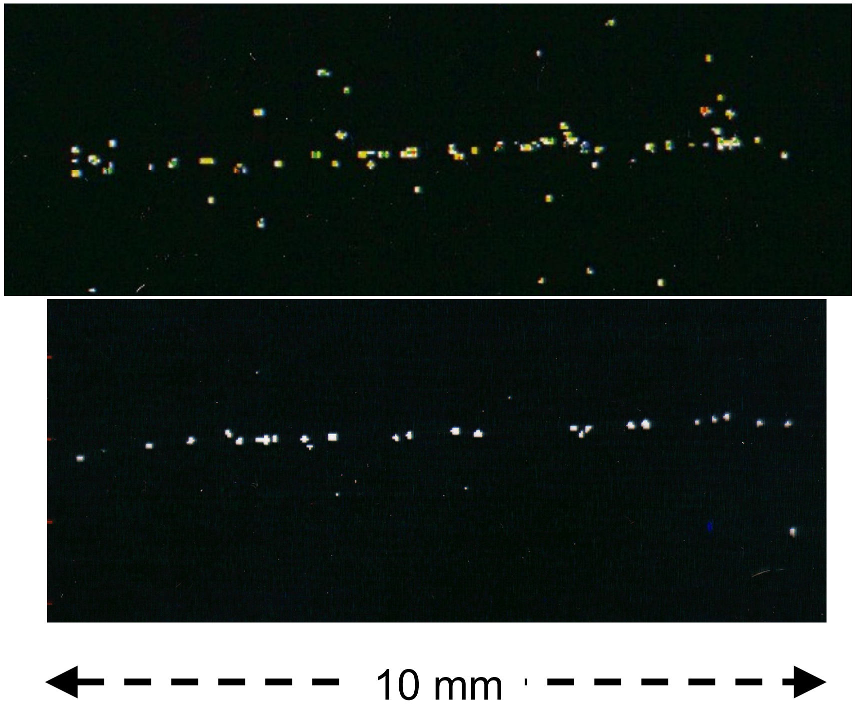
$$\theta \le \arccos\frac{n_2}{n_1} \approx 69.6^\circ$$

$$\frac{d\Omega}{4\pi} = 0.5\,(1-\cos^2\theta) \approx 5.3\%$$

Small diameter scintillating fibres

Developed in RD7, they consist of bundles of hexagonal fibres (typ. 60 μm dia., 2.5 mm bundle size)





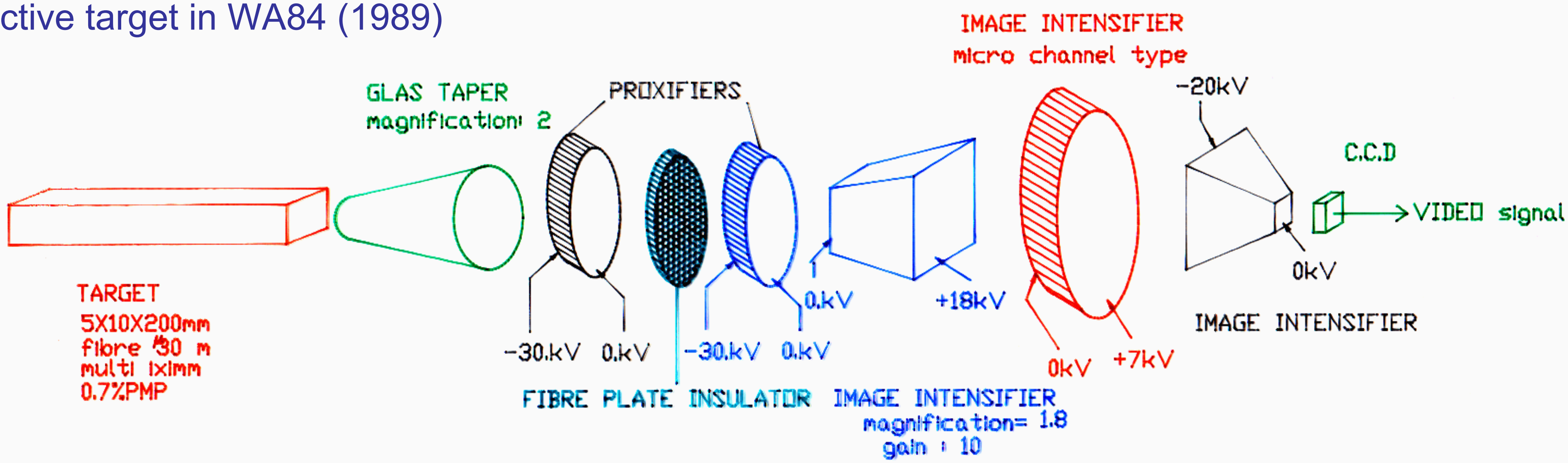
Images of tracks from 5 GeV/c pions (1989)

Beautiful tracks with only **2.2% of X_0 and >20 hits**, but…

Small diameter scintillating fibres readout

The readout of fibres is a key point for the whole system

Active target in WA84 (1989)

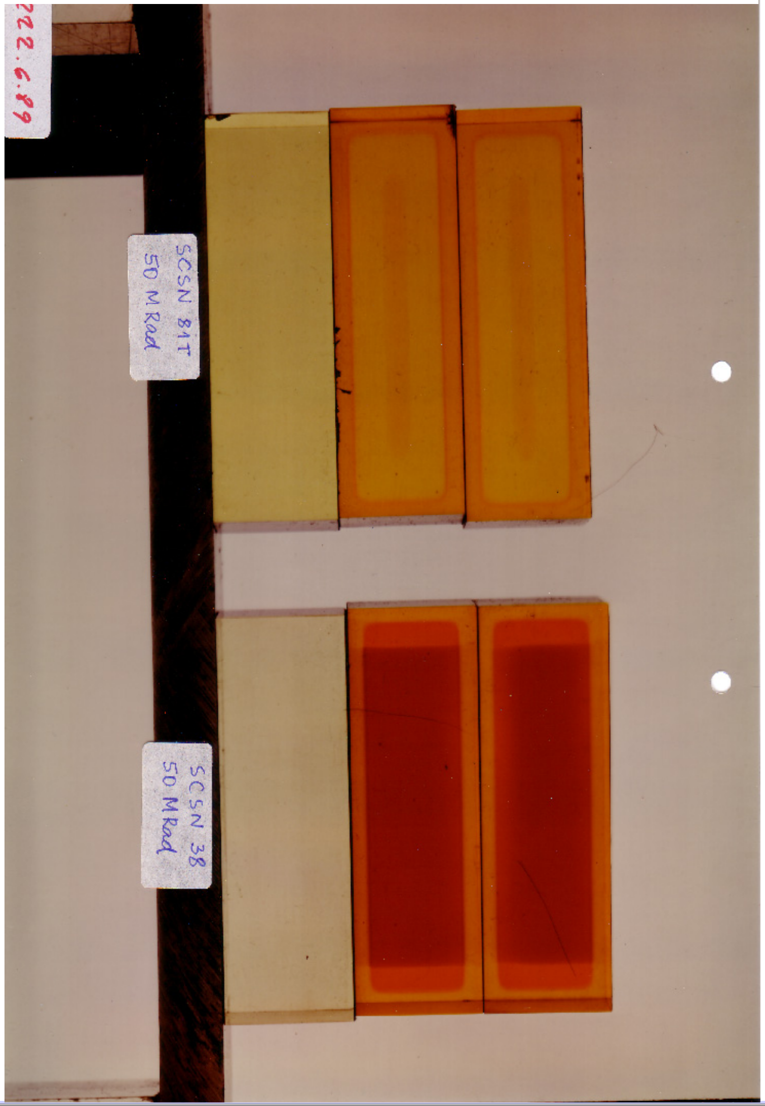


For a tracker, the readout has to match the high granularity of the fibres and bunch crossing time, but stay in the experiment's budget, size, etc.: **a real challenge.**

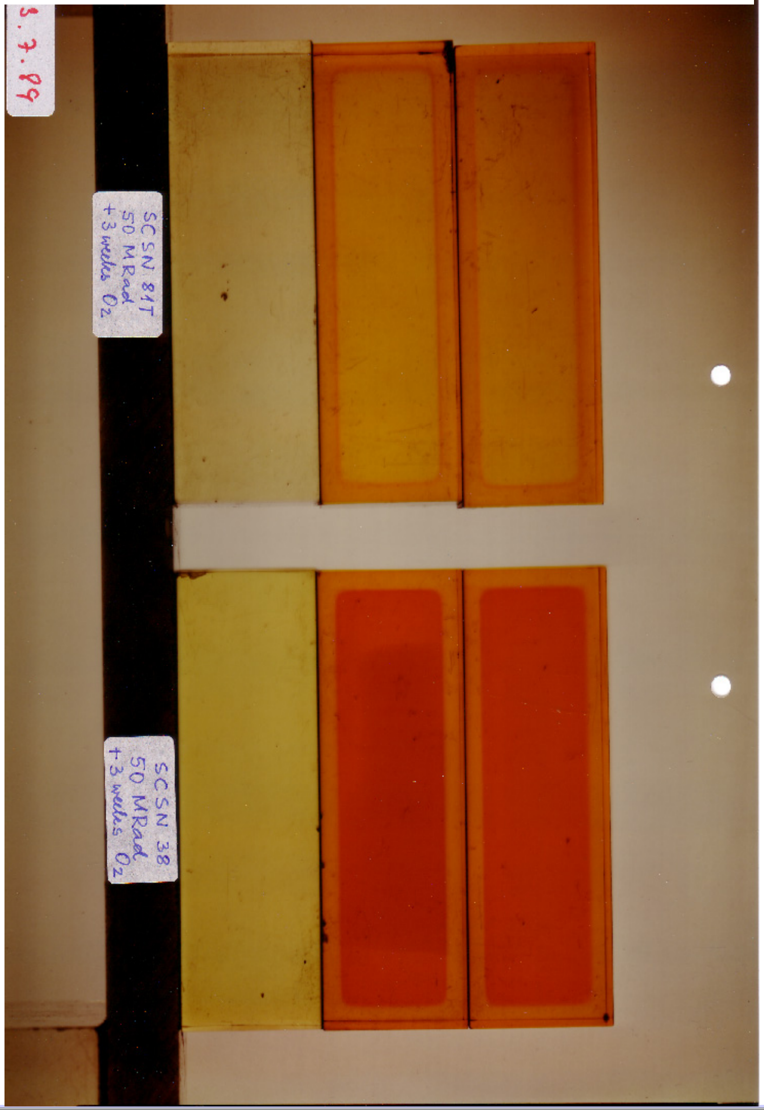
The ISPA tube was especially developed for this (see Thierry's talk)

Radiation Hardness in Plastic

500 kGy irradiation of SCSN81T and SCSN38 from Kuraray



and after 3 weeks recovery in an oxygen-rich atmosphere



R&D on organic scintillators

- New dopants with better light yield and larger Stokes shift
- High granularity readout of fibres
- Larger attenuation lengths in plastic fibres
- New radiation hard plastics to stand 100 kGy/year dose

References

- Crismatec, “*Catalogue of Scintillation Detectors*”, Saint-Gobain (1992);
- G. F. Knoll, “*Radiation detection and measurement*” ; 3rd ed., New York, Wiley, 2000;
- C. D’Ambrosio et al., “Low dose-rate irradiation set-up for scintillating crystals”, NIM A, V. 388,1-2, (1997);
- C. D’Ambrosio et al., “A HPMT based set-up to characterize scintillating crystals”,NIM A, V. 434, 2-3, (1999);
- M. Moszynski, “Inorganic scintillation detectors in γ-ray spectrometry”, NIM A, V.505, 1-2, (2003);

- J. B. Birks, “*Scintillation counters*”, Pergamon Press, (1954) London;
- I. B. Berlmann, “*Handbook of fluorescence spectra of aromatic molecules*” ; 2nd ed., Academic Press, (1971) New York
- H. Leutz,”Scintillating Fibres”, NIM A, V. 364, (1995) 422;
- RD7, DRDC Status Reports, CERN, Geneva;
- ATLAS Technical Design Report, CERN, (1999);
- C. D’Ambrosio and H. Leutz, “Hybrid photon detectors” NIM A, V.501, 2-3, (2003);