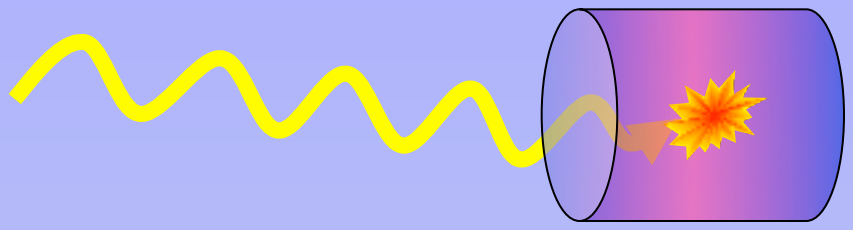
Experimental Techniques for Nuclear and Particle Physics

Introduction to scintillators

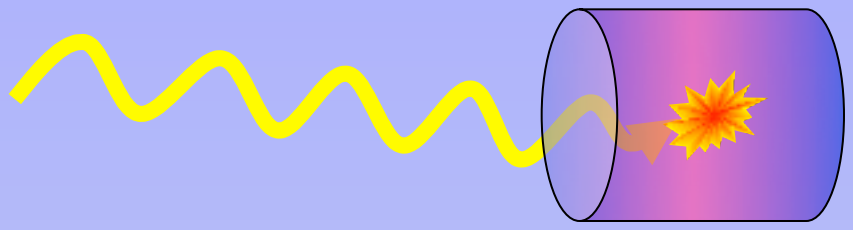
Scintillators



Properties:

- Should convert the kinetic energy of charged particles into detectable light with high efficiency
- The conversion should be linear
- The medium should be transparent to the wavelength of its own emission for good light collection
- The decay time of the induced luminescence should be short so that fast signal pulses can be generated
- The material should be of good optical quality and subject to manufacture in sizes large enough to be of interest
- Its index of refraction should be near that of a glass ($n \approx 1.5$) to permit efficiency coupling of the scintillation light to a photomultiplier tube or other light sensor

Scintillators



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.

Light yield - number of emitted photons/MeV
10 - 120 000 photons/MeV
λ – wavelength of the emitted light
typically 200 – 700 nm (UV –visible red)
Time constant for the emitted light
~ 0.6 ns – 100 μs

Scintillation materials: Both organic and inorganic materials
Can be in solid, liquid or gaseous state

- Inorganic scintillators

Best light output and linearity but slow in their response time

Intrinsic crystals

BaF_2, $CdWO_4$, CsF, etc

Doped crystals

NaI(Tl), CsI(Tl), ZnSe(Te), LSO(Ce), $LaBr_3$(Ce) etc

- Organic scintillators

Generally faster but yield less light

Plastic

Liquid scintillators

Some crystals show two or more light components with different wave lengths and time constants.

Typical scintillator properties compared to semicionductor detectors

Solid state detectors	**Scintillators**
Si, Ge	
+ good energy resolution	- poor energy resolution
~ 0.1 %	
+ electronic segmentation	typically > ~5 % at best
- slow	+ fast – slow
- low stopping power	+ high – low stopping power
wide bandgap semiconductors	*new materials*
CdTe, CdZnTe, HgI_2	e.g. $LaBr_3(Ce)$
+ high stopping power	
+ electronic segmentation	+ high light yield (~70 ph/keV)
- energy resolution ~ 1 %	
	+ energy resolution ~ 3 %
	+ fast (τ~20ns)

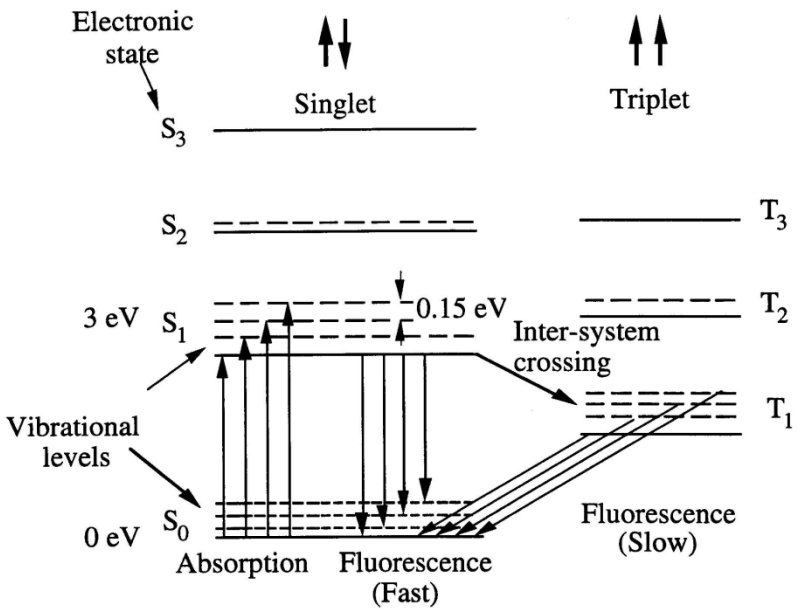
Organic scintillators

plastic scintillators

liquid scintillators

- The states of interest are energy levels of individual molecules, i.e. no interactions with neighbours.
- excitation and emission spectra practically the same whether in solid, liquid or gaseous state.
- Low stopping power for gamma radiation.
- **Mostly used for detection of neutrons and charged particles.**

Typical energy levels



a) At room temperature practically all electrons in ground state. (since energy of S_1 states >> 0.025 eV)

b) Incident radiation populates S_1 states

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

c) S_1 can also decay to adjacent triplet levels.
Since their energy is significantly lower, the decay time is much longer.

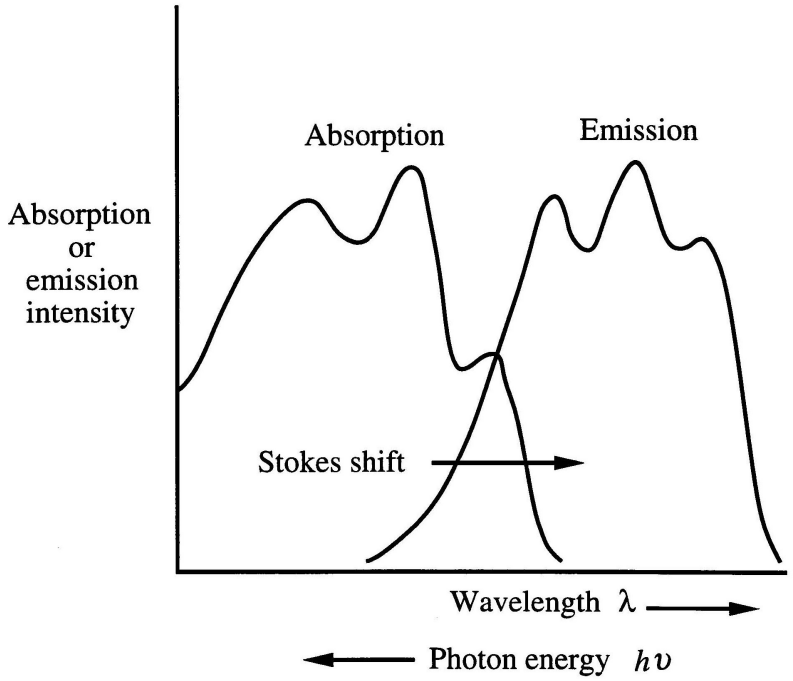
Why isn't emitted light re-absorbed?

If emission and absorption occur at the same wavelengths, most emitted photons would be absorbed within a short distance,

⇒ poor light output from large volume scintillators

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).

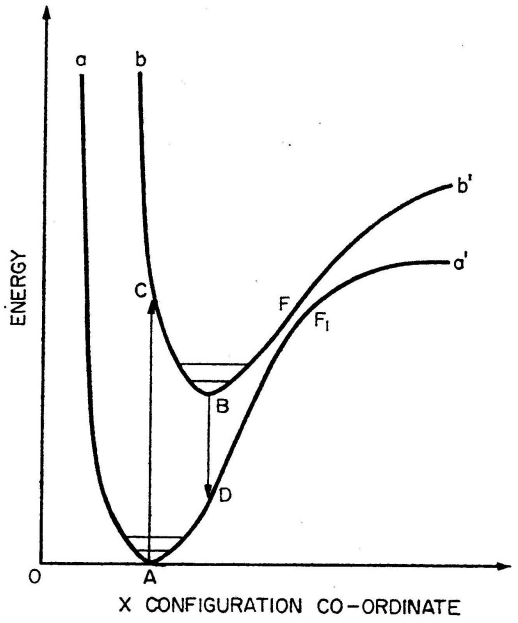
⇒ only small overlap of emission and absorption spectra



Luminescence vs Quenching

Plot energy levels in configuration space, i.e. any set of coordinates describing the configuration of a molecule.

In general, configuration space is multi-dimensional, but one example is the interatomic distance, which may change as a molecule is excited. Since electronic transitions proceed much more rapidly than rearrangement of the nuclei (or the lattice in a crystal), they are represented by vertical lines in configuration space.



(from Birks)

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

The energy released in the transitions C → B and D → A is thermally dissipated as molecular or lattice vibrations.

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

$$F \rightarrow F_1$$

can proceed without emission of a photon.

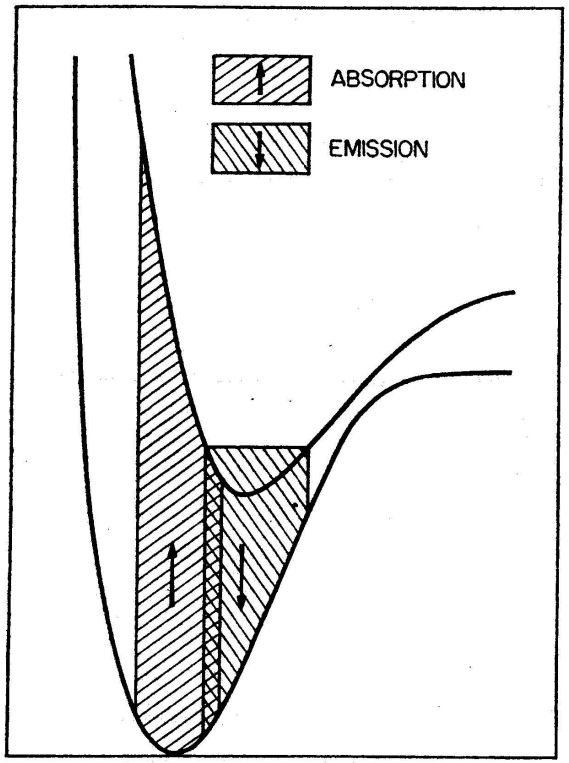
In this case the sequence following an excitation is

Excitation:	A → C
Decay to ground state:	F → F_1
thermal equilibration:	F_1 → A

This mode of decay without emission of a photon is called quenching, as it competes with the scintillation process and reduces the intensity of the emitted light.

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

Overlap of absorption and emission spectra



(from Birks)

Thermal excitation populates states near minima.
Widths of absorption and emission spectra depend on the density 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.

$\Rightarrow$ reduction in light output with increasing temperature

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

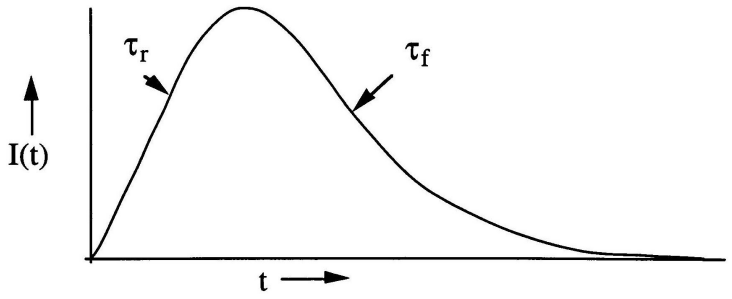
$$I(t) \propto 1 - e^{-t/\tau_r}$$

fall with time constant τ_f

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

total pulse shape

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



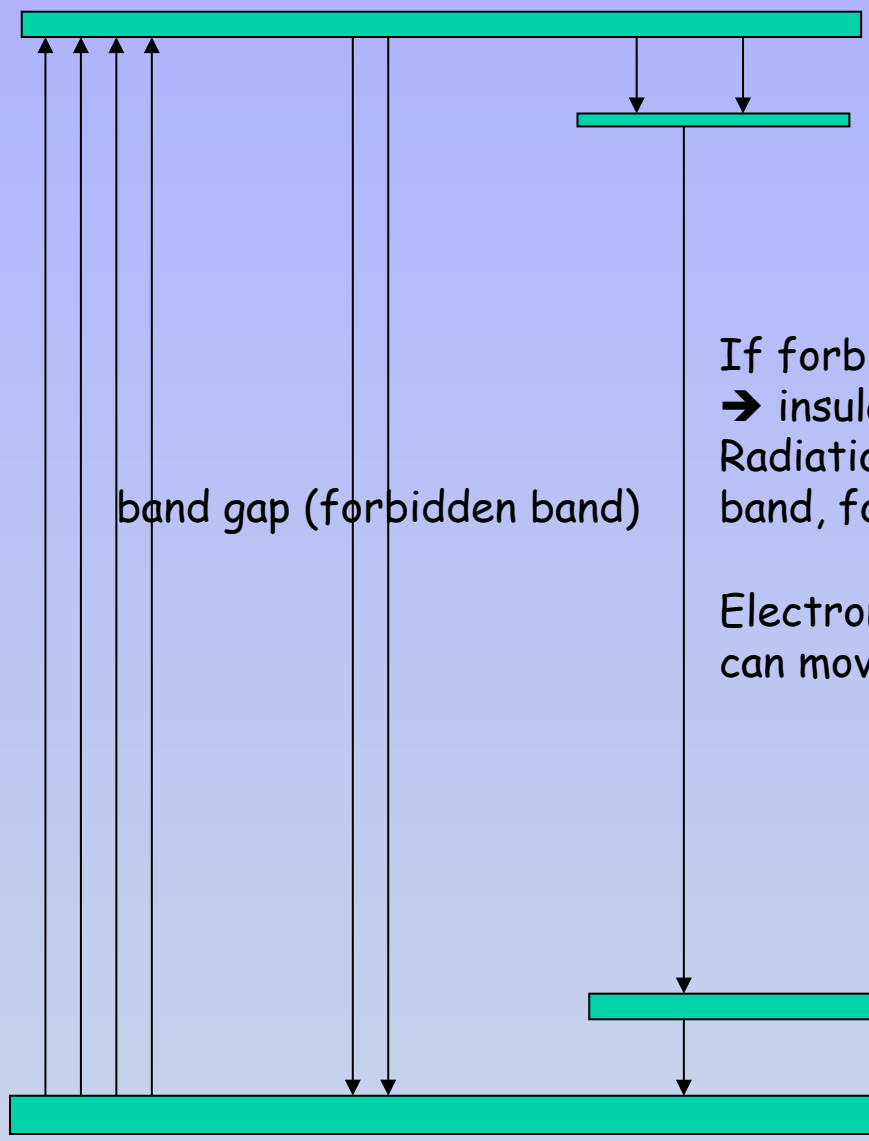
Rise time usually increased substantially by subsequent components in system and variations in path length in large scintillators.

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	$1.2 \cdot 10^4$

Pilot U, NE104 and NE102 are manufacturers' designations

Inorganic scintillators



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

Scintillation photons are emitted from activator excited states, fast transition, visible light.

Competing processes:

Electron arrives to excited states from which transition to ground state is forbidden. Additional small energy is required to lift the electron to other excited states (thermal excitation) with higher transition probability. This results in *phosphorescence radiation*, or "*afterglow*", which is a slow time component.

Some excited states cause radiationless transitions, which represents loss mechanism in the conversion of the radiation energy to scintillation light. This is the *quenching effect*.

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

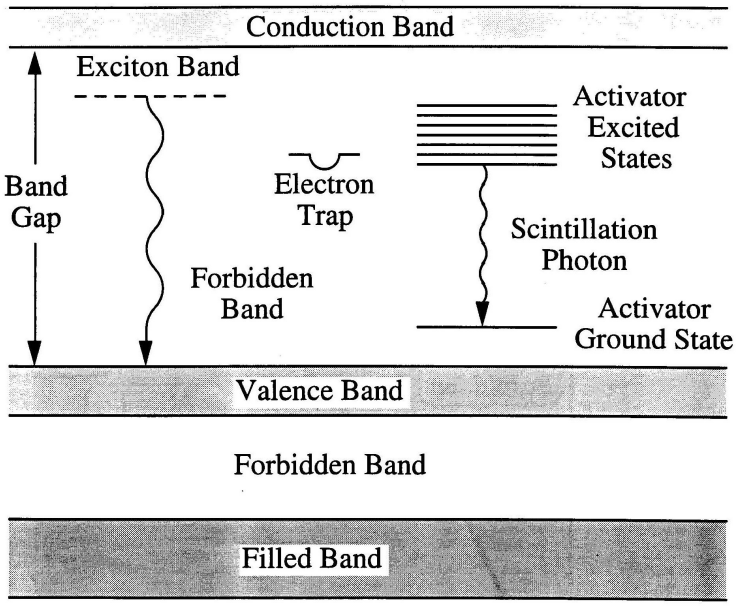
$$E_{emission} < E_g$$

Three mechanisms:

a) excitons (bound electron-hole pair)

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

c) activators
very dilute concentrations of specific atoms can greatly increase light output



(from Derenzo)

Examples:

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

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

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

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

Band gap energies in semiconductors and scintillators

	E_{gap} [eV]	$E_{e\text{-}h}$ [eV]
Si	1.12	3.61
Ge	0.74	2.98
CdTe	1.47	4.43
HgI_2	2.13	4.2
NaI(Tl)	5.9	15.3
CsI(Tl)	6.5	15.2

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, $PbWO_4$).

See http://scintillator.lbl.gov for updated and complete table

Scintillation efficiency

Energy required to generate one e-h pair

$E_{e\text{-}h}=\beta E_{gap}$ $\beta\approx 2.3$ (2-3)

CsI(Tl) $E_{gap}=6.4$ eV assume $E_\gamma=1$ MeV

Number of light photons

1 MeV/(2.3xE_{gap})= 1 000 000 eV/(2.3x6.4 eV)≈67 000 ph

compare with measured 60 000 ph

NaI(Tl) $E_{gap}=5.9$ eV

1 000 000 eV/(2.3x5.9 eV)≈73 000 ph

measured 40 000 ph

BaF_2 (fastest commercial scintillator)

fast component E_{gap}=18.0 eV

1 000 000 eV/(2.3x18.0 eV) ≈ 24 000 ph

measured 2200 ph

slow component E_{gap}=10.6 eV

1 000 000 eV/ (2.3x10.6 eV) ≈ 41 000 ph

measured 7000 ph

Most crystals show very low efficiency for the scintillation process

Scintillation process

- conversion to e-h pairs
- transfer to luminescence centre
- luminescence, i.e. photon emission

$N_{ph}=(E_\gamma/E_{e\text{-}h})SQ$

S – transfer efficiency of the e-h pair to luminescence centre

Q – efficiency for photon emission

Birk's Rule

For an ideal scintillator and low ionization density

Luminescence $\propto$ 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

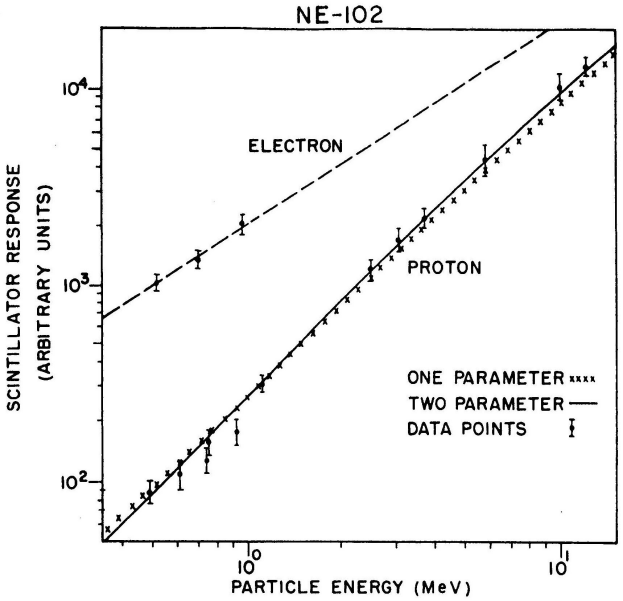
$$\frac{dL}{dr} = \frac{S\dfrac{dE}{dr}}{1 + kB\dfrac{dE}{dr}}$$

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

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

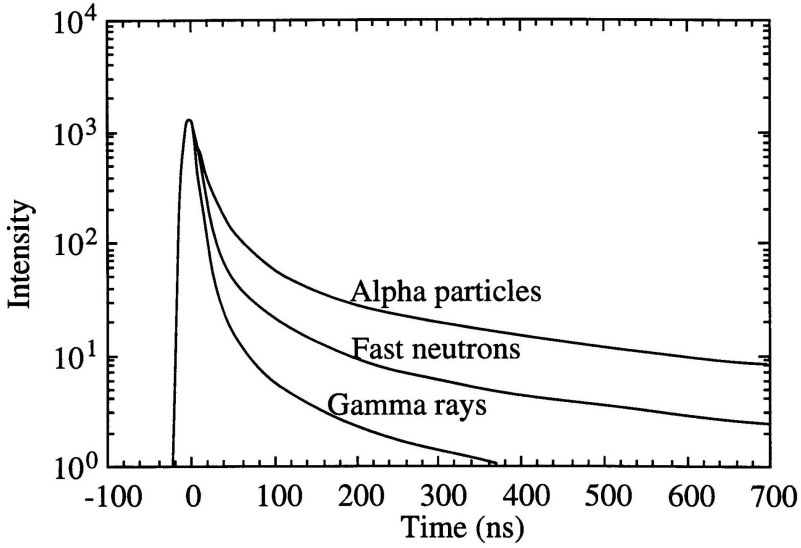
$$\frac{dL}{dr} = \frac{S}{kB} = const$$

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



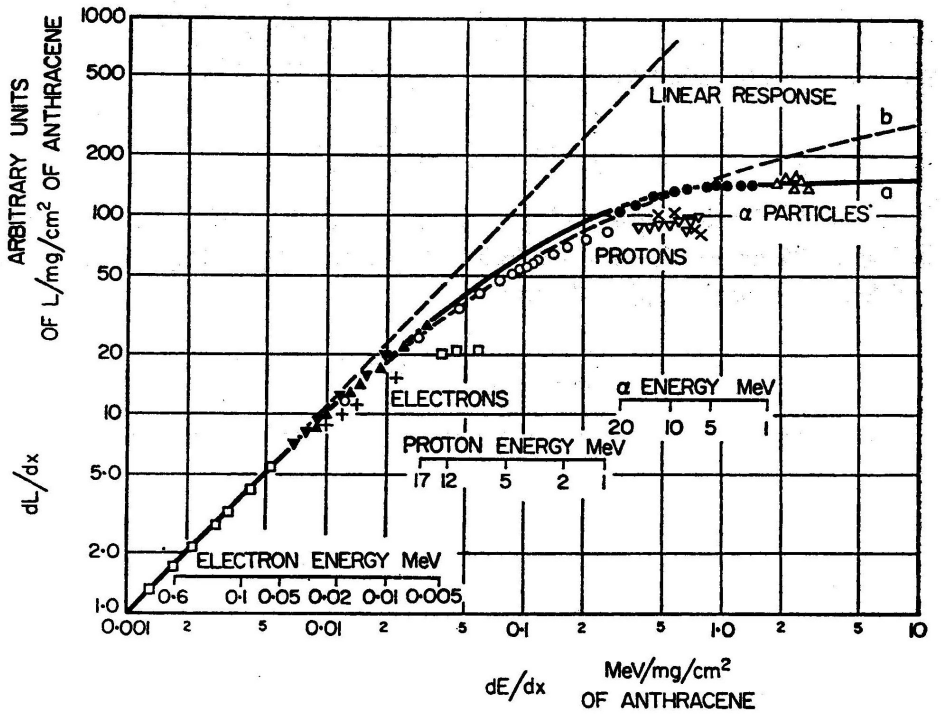
(Craun and Smith)

Decay time in stilbene for various particles



(from Bollinger and Thomas)

Variation of specific fluorescence dL/dx in anthracene with specific energy loss dE/dx



(Brooks, from Birks)

The fact that data for both weakly and heavily ionizing particles lie on the same curve of light output vs. dE/dx, shows that the reduction in light output depends on ionization density.

Interpretation:

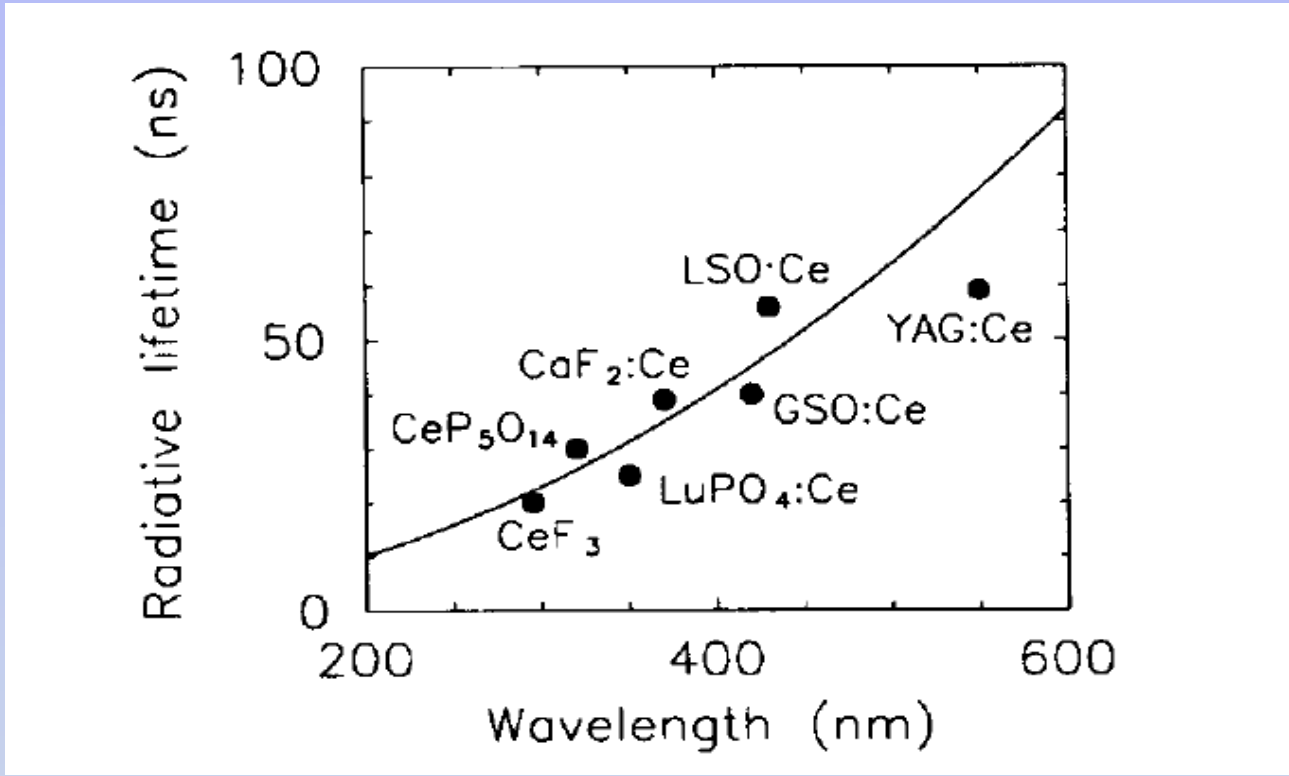
For lightly ionizing particles, e.g. electrons, the spacing between successive ionizations is several molecular distances, so the interaction between ionization sites is negligible.

Heavily ionizing particles lead to overlapping excitations, which tends to increase quenching.

Decay times

Radiative decay time for electric dipole emission

$\tau_r \sim \lambda^2$

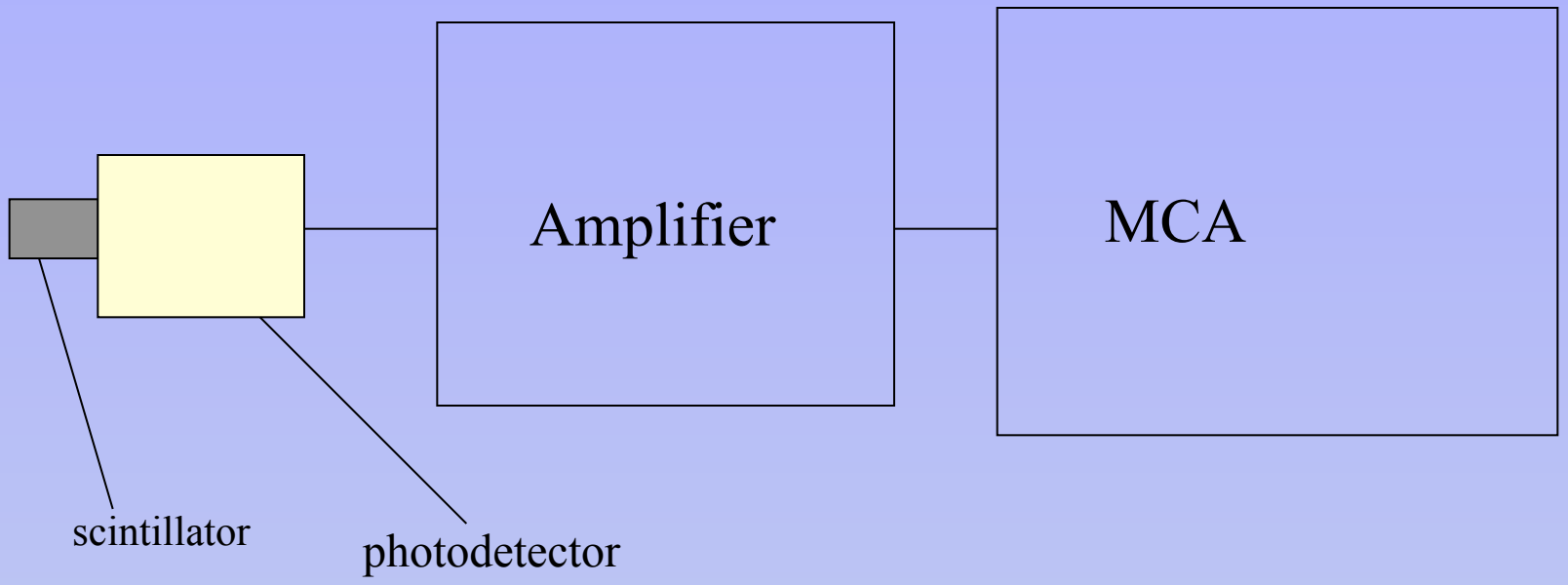


Tradeoff: timing – energy resolution

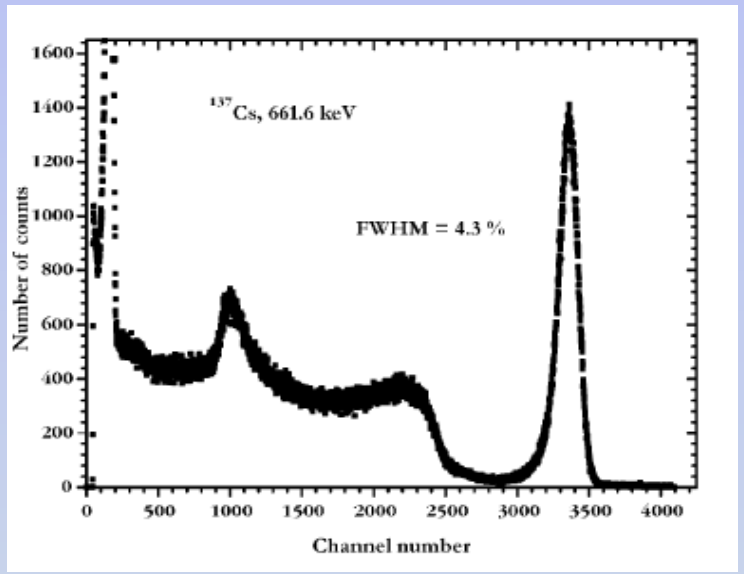
High light yield → low energy gap crystals → long wavelength of the scintillation light

Fast crystals → short wavelength (UV region) → high energy gap

How to measure light yield



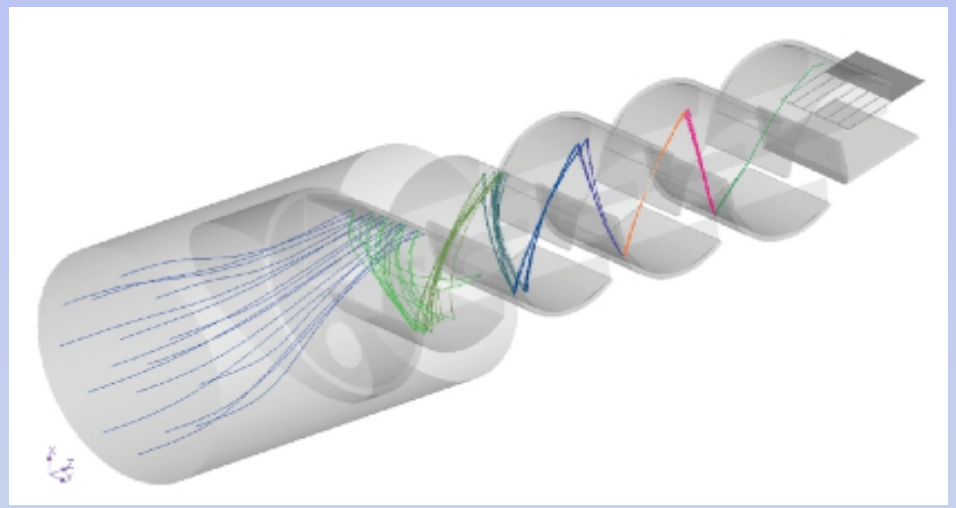
PIN photodiode
Photomultiplier (PM-tube)
avalanche photodiode



Photomultiplier

These detectors multiply the current produced by incident light by as much as 100 million times in multiple dynode stages, enabling individual photons to be detected when the incident flux of light is very low

Photocathode: convert light photons into low energy electrons (photoemission)



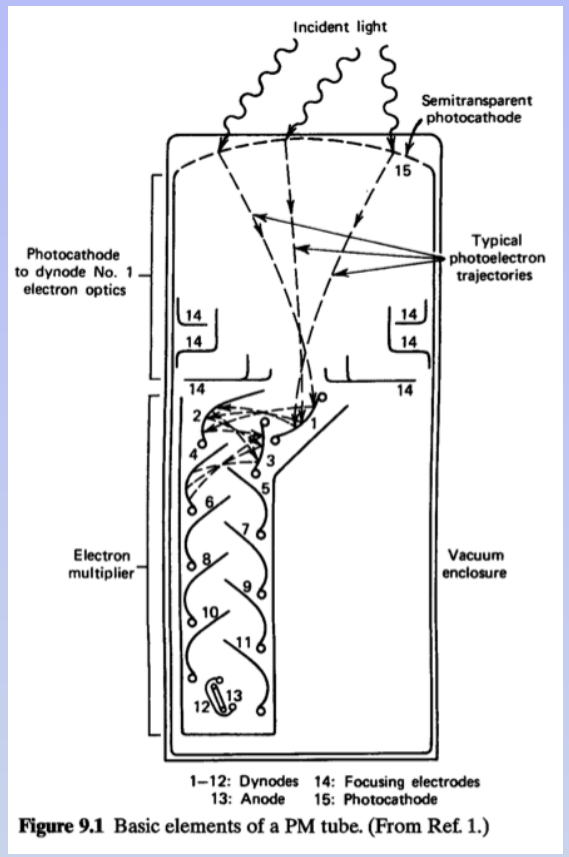


Figure 9.1 Basic elements of a PM tube. (From Ref. 1.)

Photomultiplier

$$N_{photons} = N_{phe} / Q.E(\lambda)$$

number of photons entering PM-tube

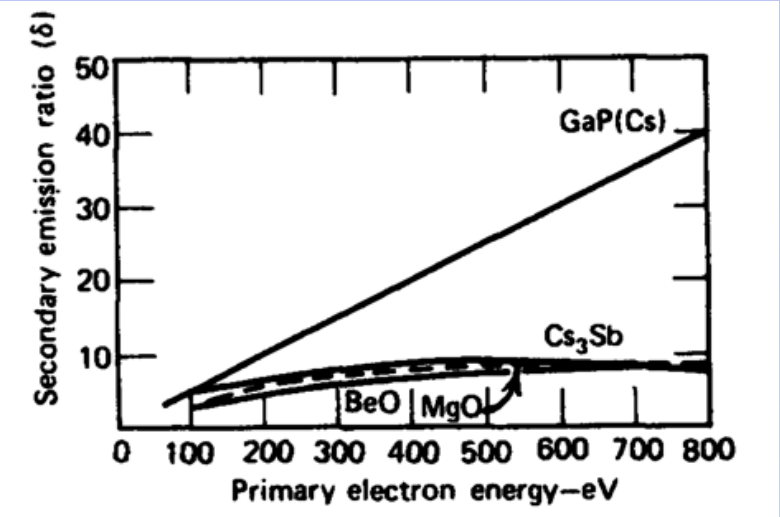
number of photoelectrons emitted from the photocathode

Quantum Efficiency

Quantum efficiency around 20-30 %
Strong function of the wavelength of the incident light

Secondary electron emission
Overall multiplication factor:
δ = n° of secondary electrons emitted/ primary incident electron

Gain of the PM = $\alpha\delta^N$

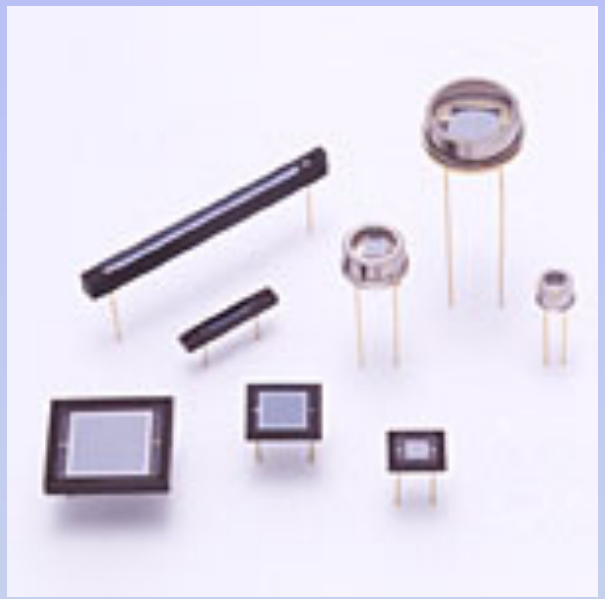


Photodiodes

Higher quantum efficiency
Lower power consumption
Compact size
Insensitive to magnetic fields

$$N_{photons} = N_{e\text{-}h} / Q.E(\lambda)$$

number of electron-hole pairs



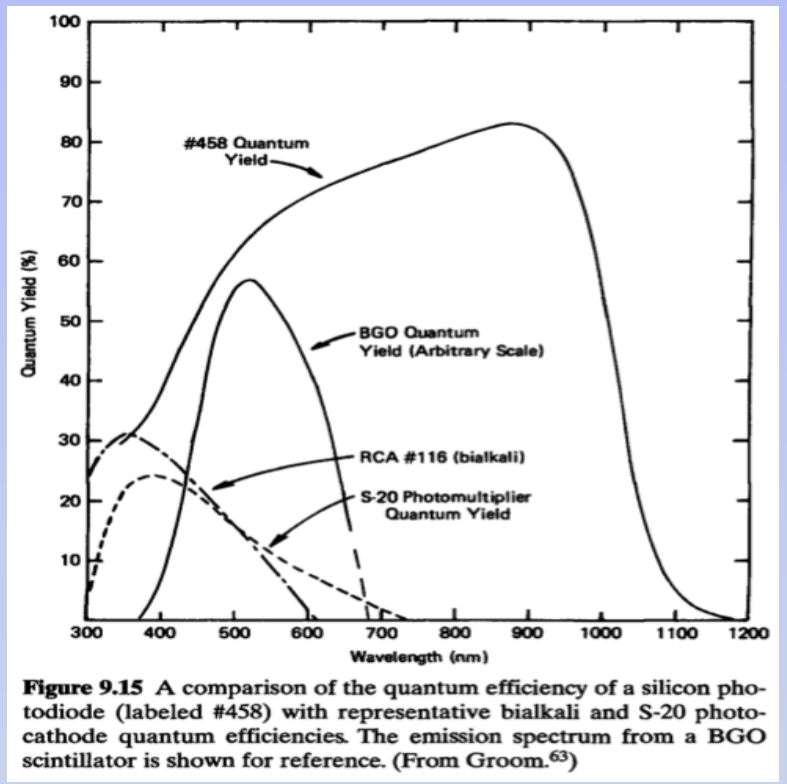


Figure 9.15 A comparison of the quantum efficiency of a silicon photodiode (labeled #458) with representative bialkali and S-20 photocathode quantum efficiencies. The emission spectrum from a BGO scintillator is shown for reference. (From Groom.[63])

Energy resolution

$(\Delta E/E)^2=(\delta_{intr})^2+(\delta_{st})^2+(\delta_n)^2$

δ_{intr} – intrinsic resolution of the crystal

δ_{st} – statistical contribution

δ_n – dark noise contribution

For PM-tubes

$\delta_{st}=2.35x(1/N_{phe})^{1/2}x(1+\varepsilon)^{1/2}$

ε – variance of the electron multiplier gain

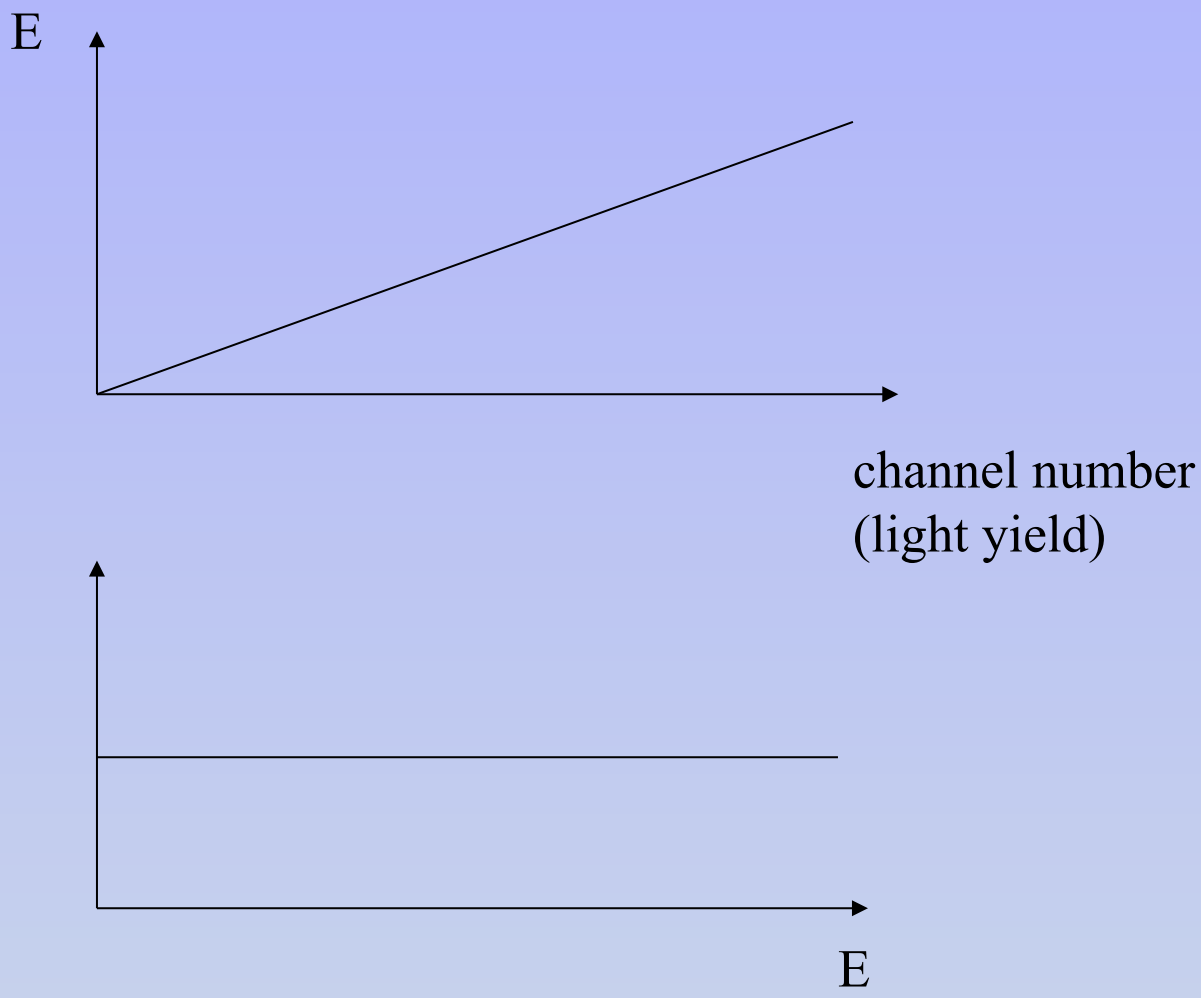
For avalanche photodiodes (APD)

$\delta_{st}=2.35x(F/N_{e\text{-}h})^{1/2}$

F – excess noise factor, reflecting statistical fluctuation of the APD gain

Energy resolution strongly depends on N_{phe}, alt. $N_{e\text{-}h}$

Light yield non-proportionality
ideal case:



Light yield non-proportionality

This assumption is based on two requirements:

(1) the light output of the scintillator is proportional to the energy of the incident radiation;

(2) the electrical pulse produced by the photomultiplier tube is proportional to the emitted scintillation light.

In real life

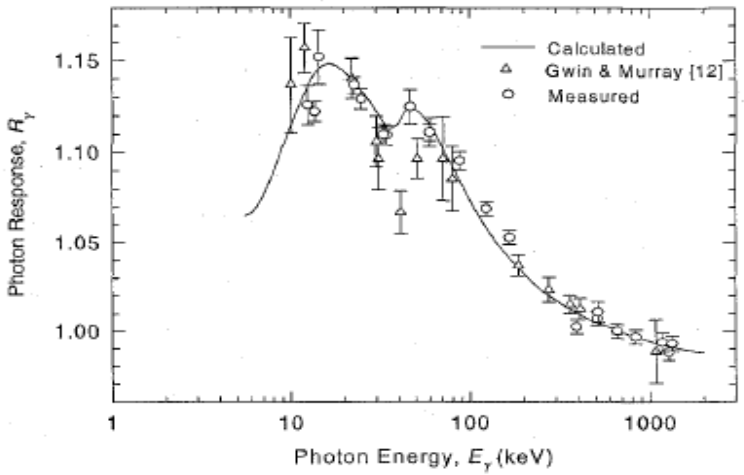


Figure 4: CsI(Tl) calculated and measured photon responses $R_\gamma(=L_\gamma/E_\gamma)$. Results from Gwin and Murray [12] have also been included. Data are normalized to unity at 661.66 keV.

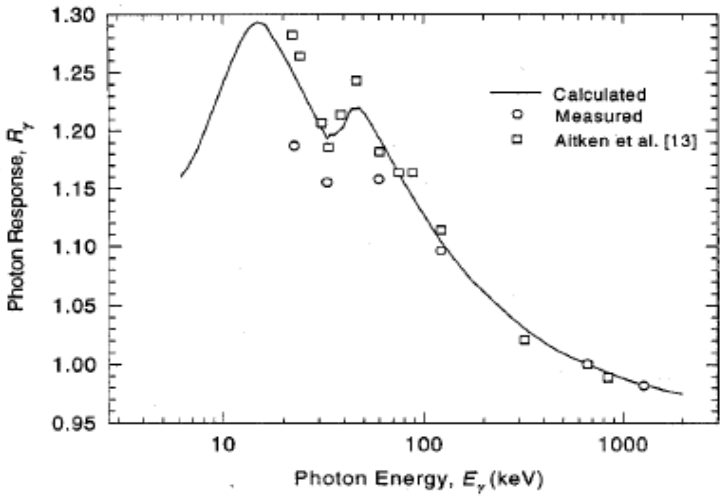
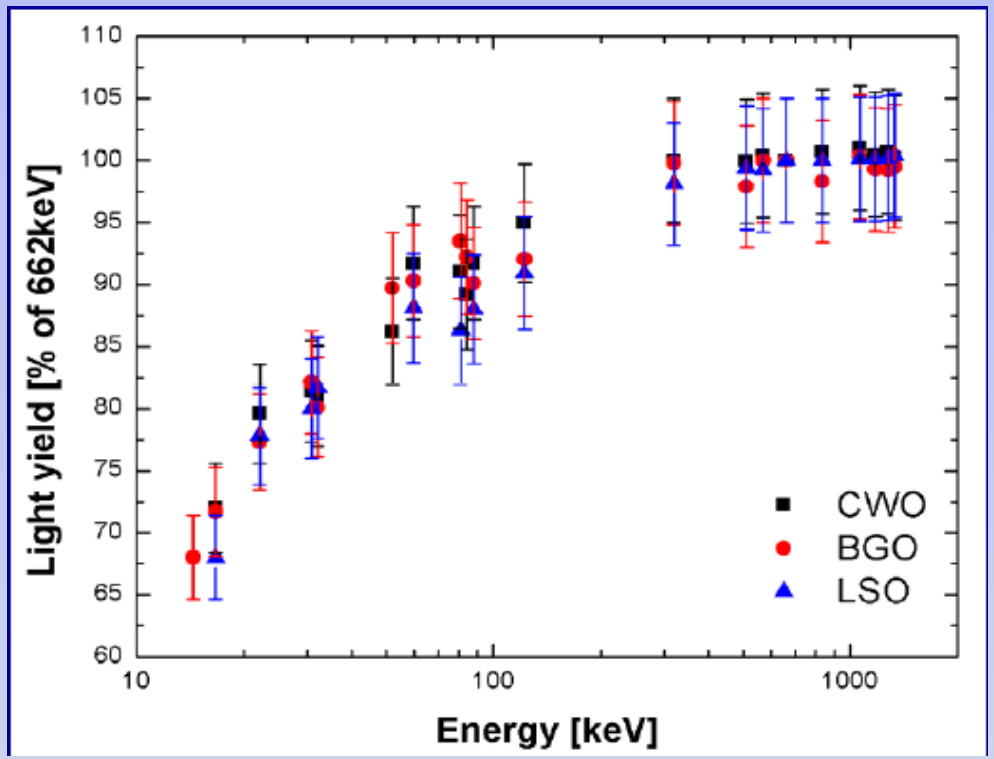
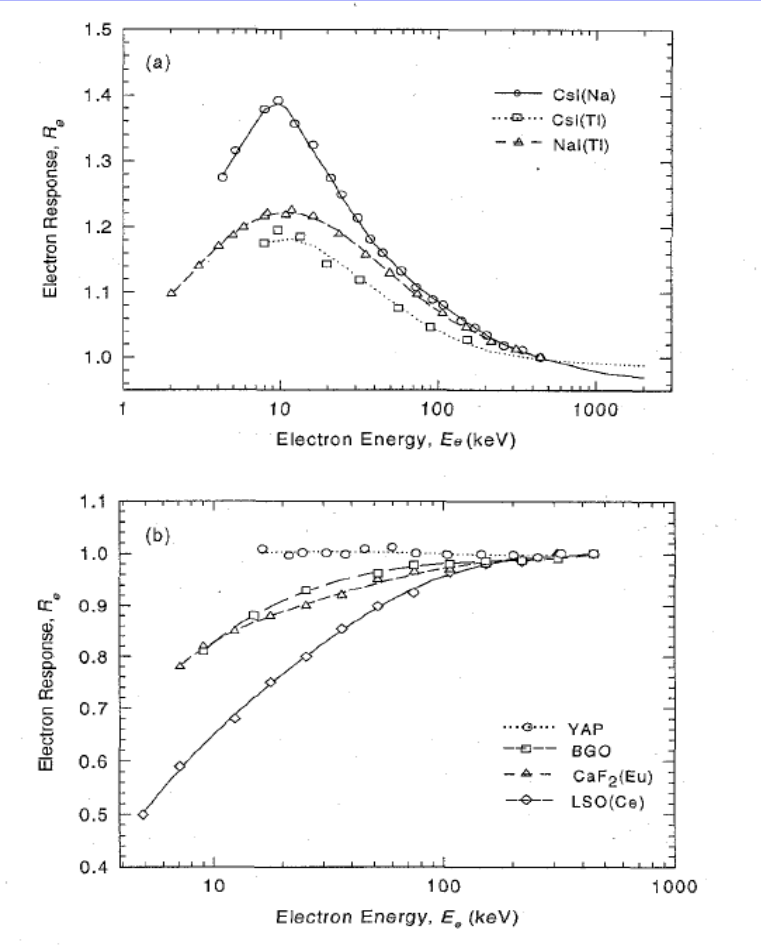


Figure 6: Calculated and measured CsI(Na) photon responses $R_\gamma(=L_\gamma/E_\gamma)$ including results from Aitken et al. [13]. Data are normalized to unity at 661.66 keV.

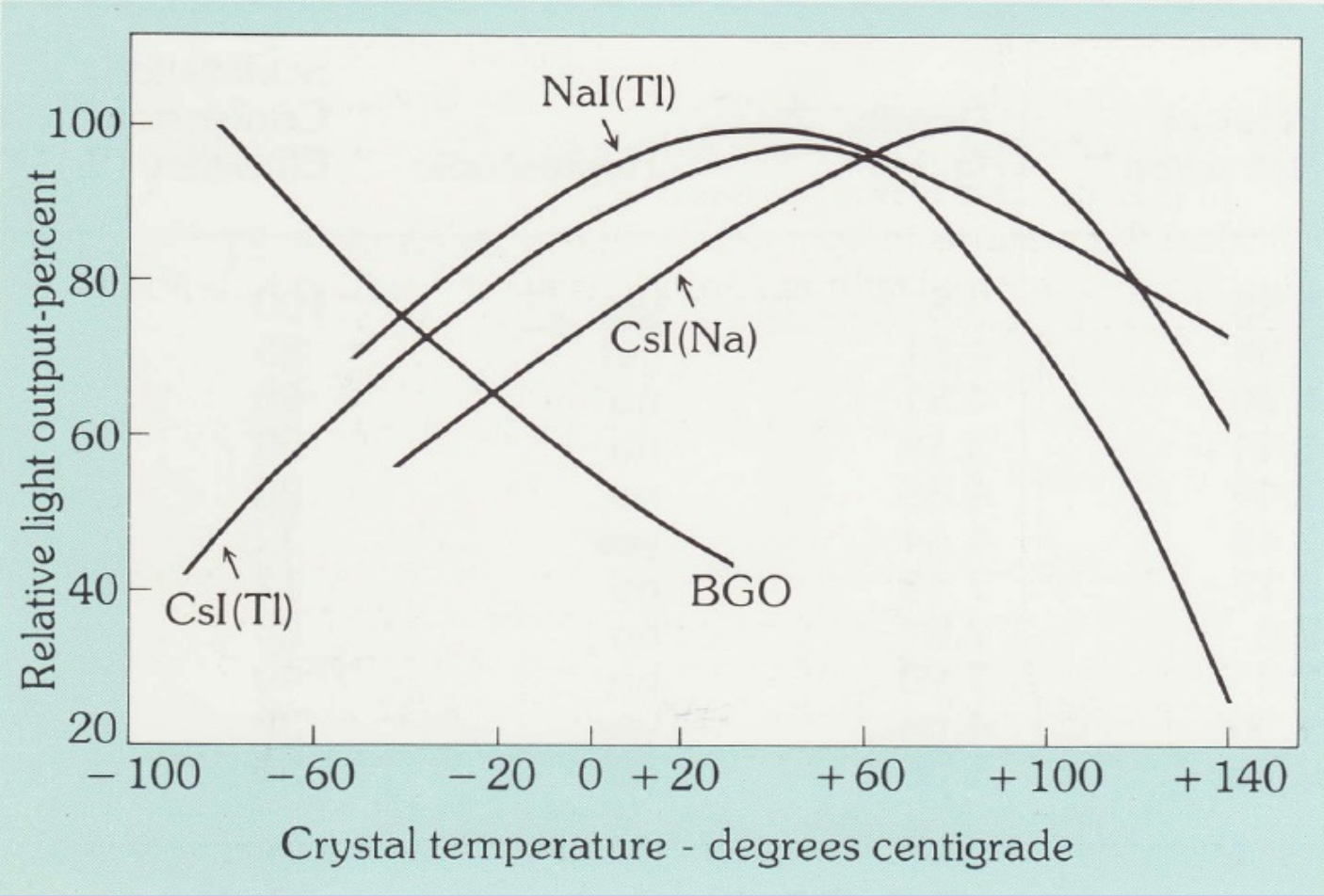


Electron response



Most scintillators show light yield non-proportionality, due to non-proportional electron response.

Temperature dependence



In organic scintillators the light output is practically independent of the temperature between -60° and 20°

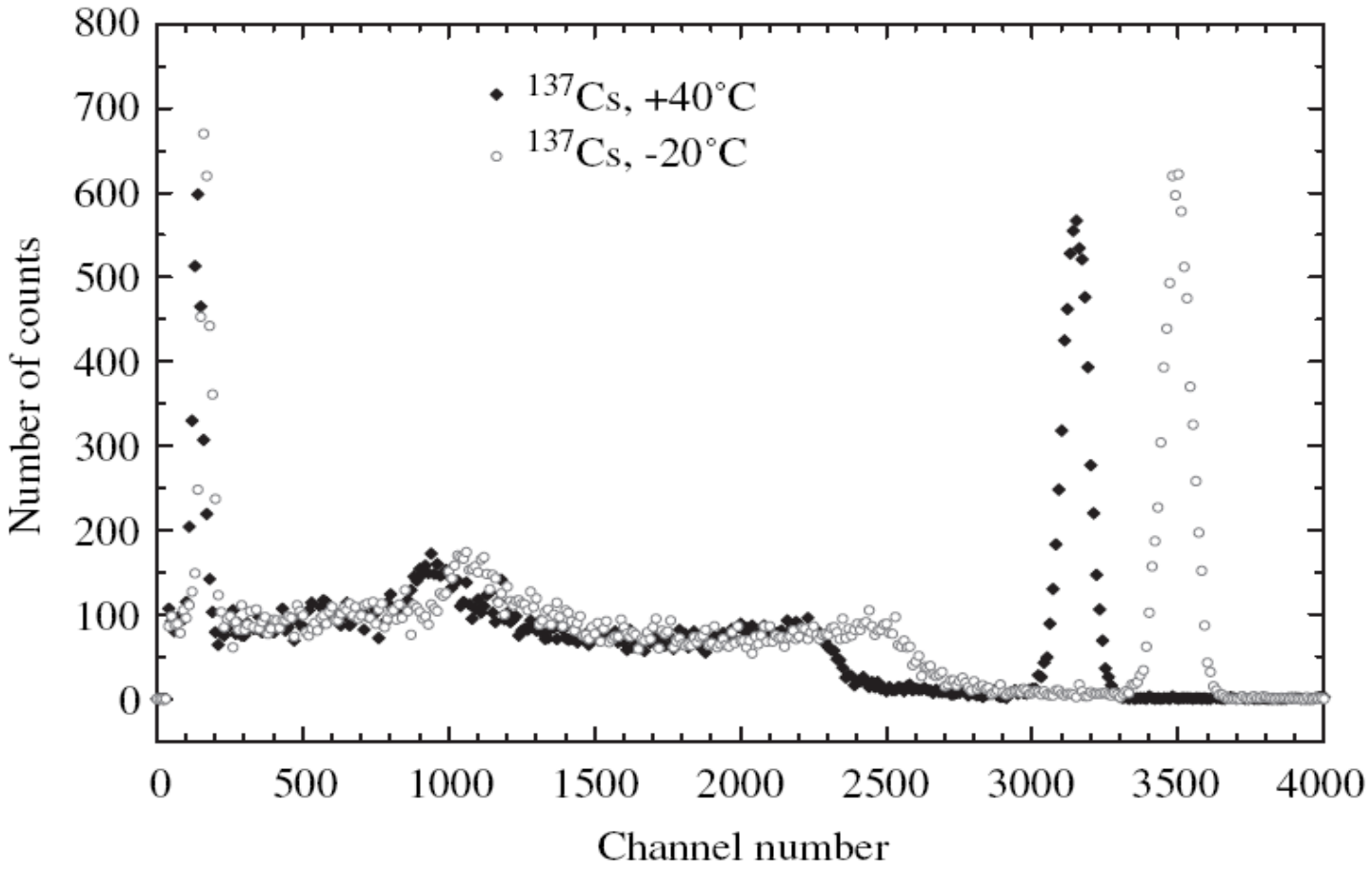


Fig. 5. The energy spectra of γ-rays from a ^{137}Cs source measured with the $LaBr_3$ crystal at −20 and 40 °C temperatures.

	room temp.		*LN_2 temp.*	
	energy resolution [%]	light yield [ph/MeV]	energy resolution [%]	light yield [ph/MeV]
pure NaI	16.5	3800	4.3	84 000
BGO	10.0	6900	6.5	29 000
pure CsI		2000	4.3	124 000

CsI(Tl)

Number of light photons

1 MeV/(2.3x$E_{gap)}$= 1 000 000 eV/(2.3x6.4 eV)≈67 000 ph

compare with measured 60 000 ph

Dopants

	λ [nm]	τ [ns]	light yield [ph/MeV]
undoped CsI	315	16	2000
CsI(Tl)	540	800/6000	60 000
CsI(Na)	420	630	37 000
CsI(CO_3)	405	2000	26 000

Particle identification

- Light yield depends on the charge, mass and energy of the detected particles
- For some scintillators with two light components (fast and slow components) the amplitude ratio of the two components varies with the particle types and there is a change in the decay constant with the density of ionization of the particle, mainly the short decay constant, e.g. CsI(Tl).

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

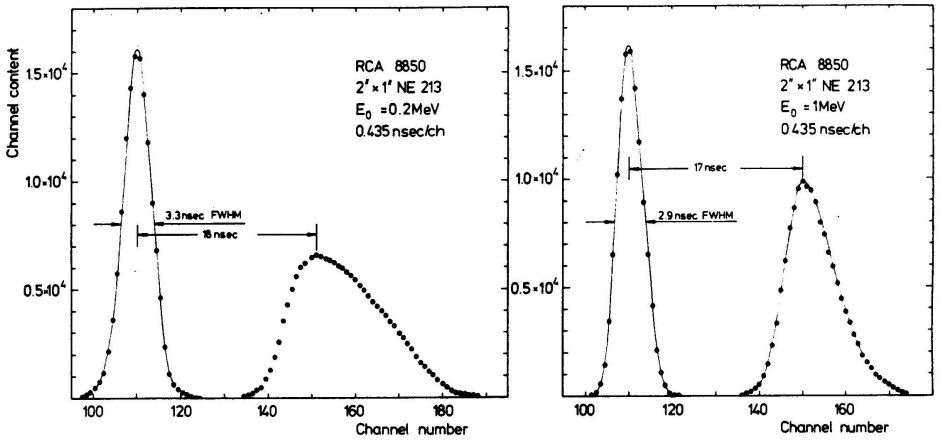


Fig. 5. Neutron–gamma timing distributions with a small scintillator (2″ diam. × 1″) for two threshold energies.

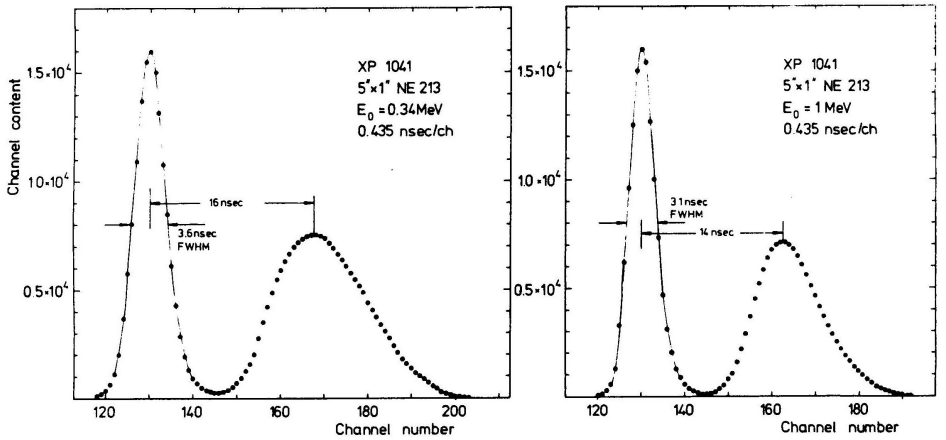
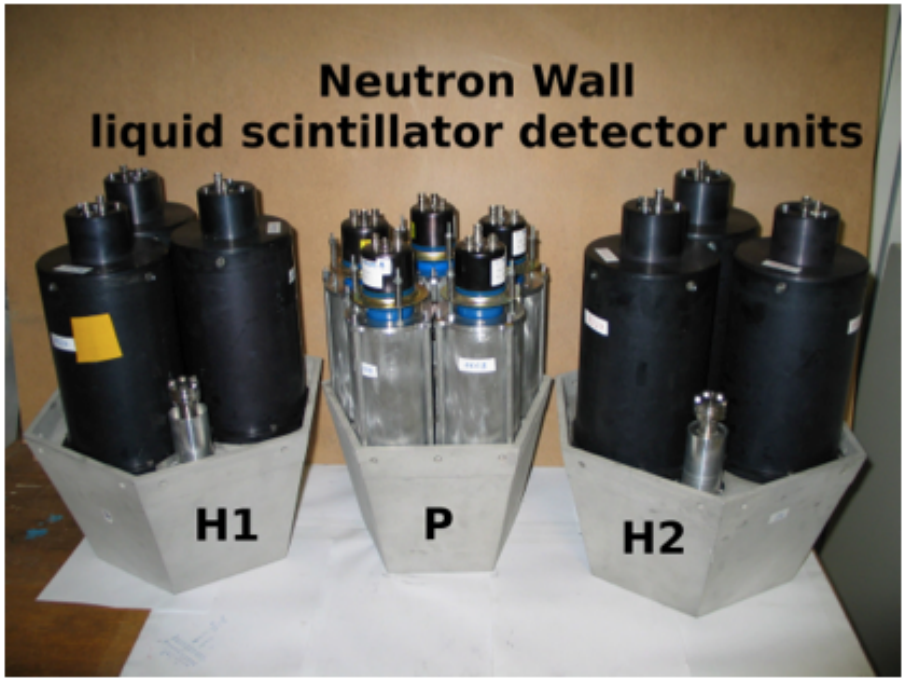


Fig. 6. Neutron–gamma timing distributions with a 5″ diam. × 1″ scintillator for two threshold energies.

Neutron Wall detectors



- Liquid scintillator = BC-501A
- Hexagonal detectors (H1,H2):
  - H1: 10 units
  - H2: 5 units
  - 3 segments/unit
  - 3.2 liters/segment
  - 1 PMT/segment: XP4512PA
- Pentagonal detector (P):
  - 1 unit
  - 5 segments/unit
  - 1.1 liters/segment
  - 1 PMT/segment: XP4312B
- Detector "thickness" ≒ 15 cm

Neutron-gamma discrimination

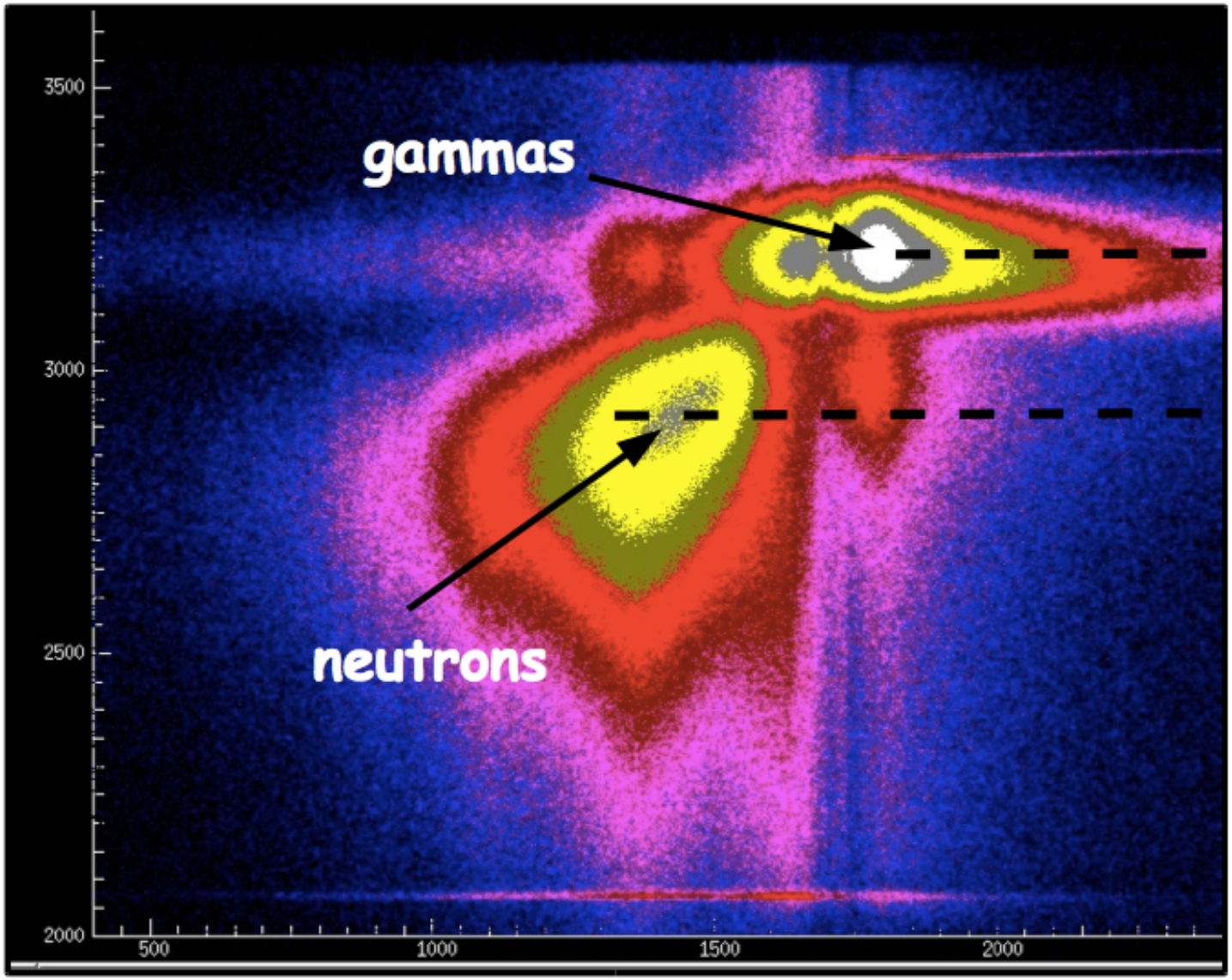
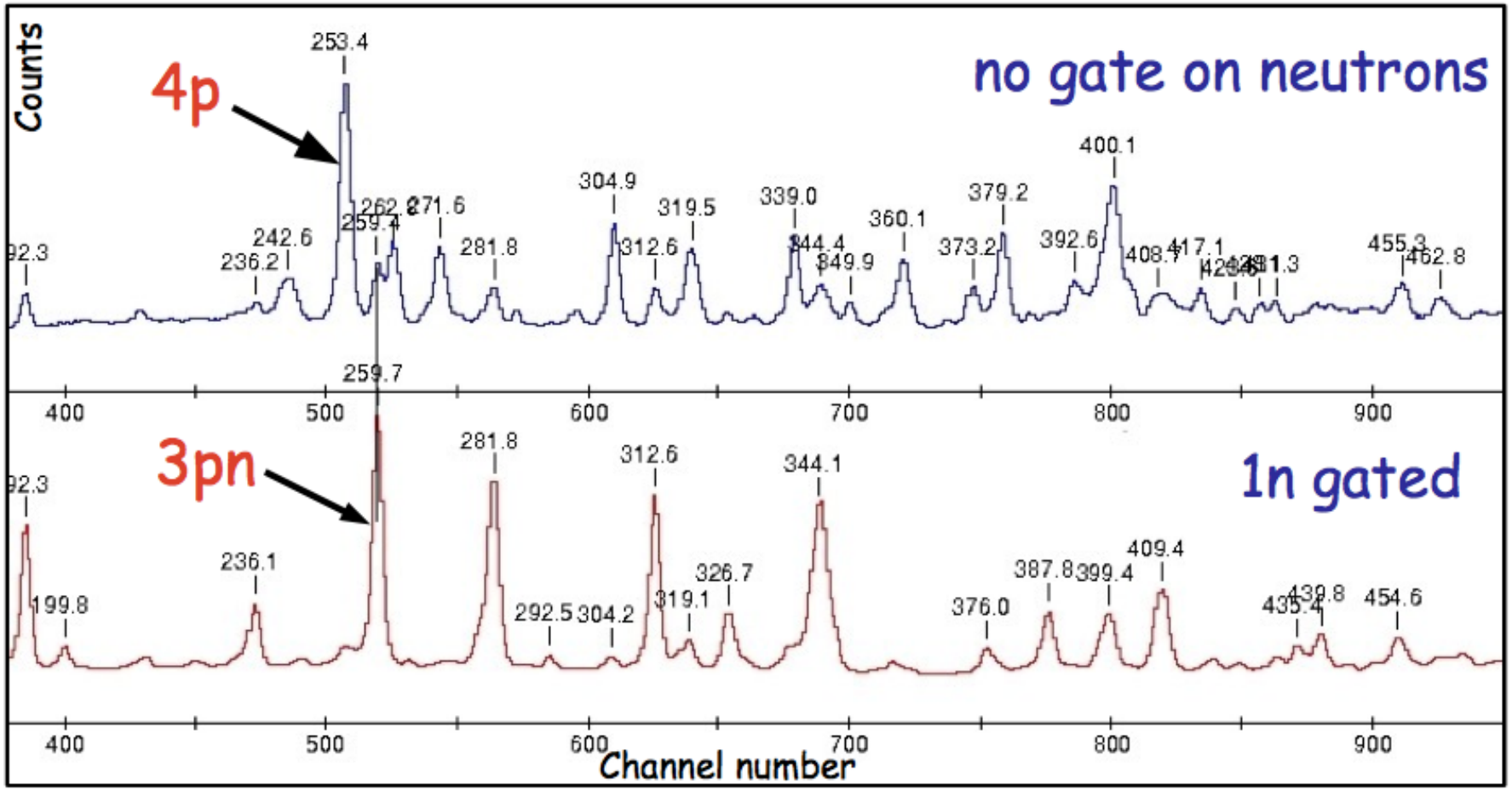


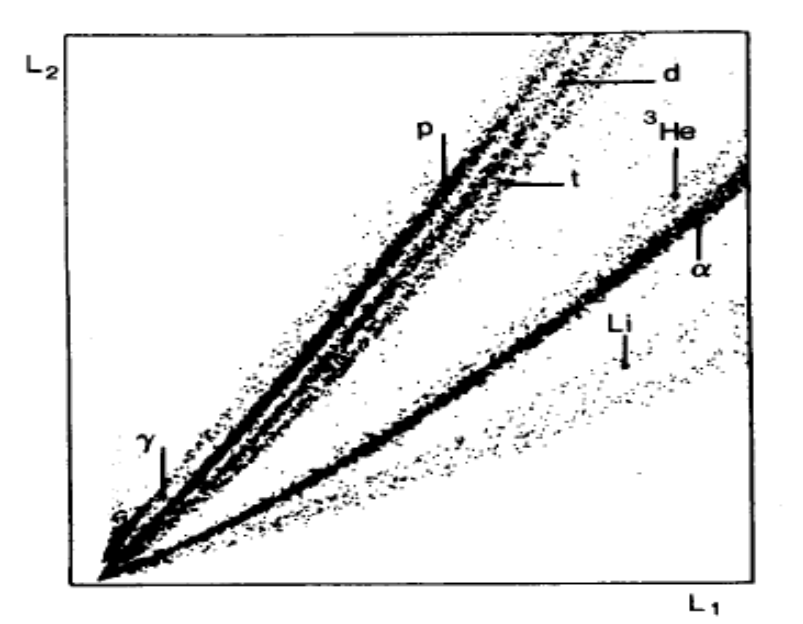
Figure by M. Palacz

Efficiency in fusion-evaporation reaction

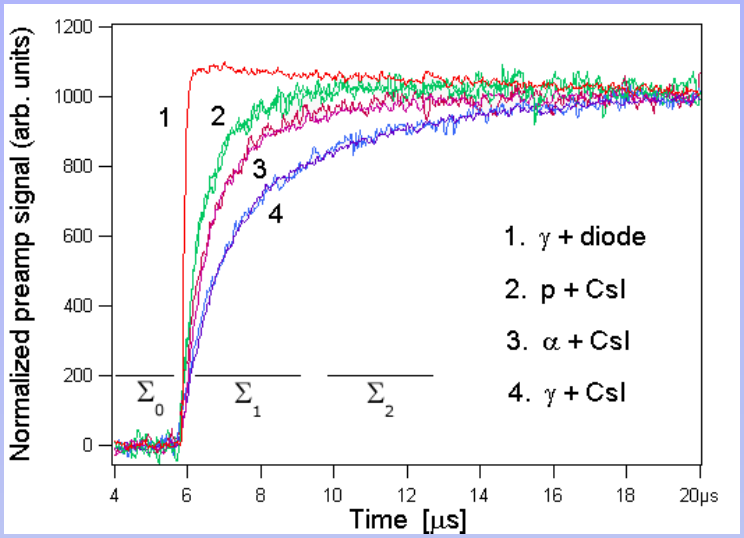
EXOGAM experiment: ^{58}Ni (240 MeV) + ^{54}Fe

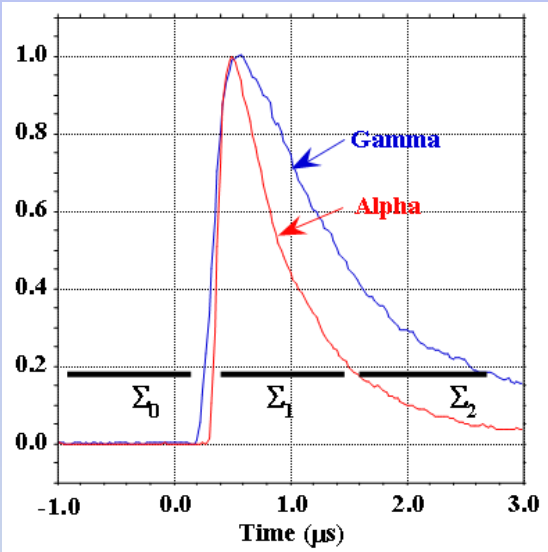


CsI(Tl) has intrinsic particle discrimination properties due to its different decay components



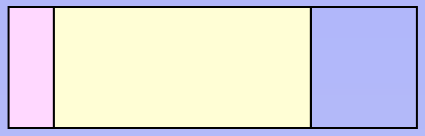
CsI(Tl)





L_1, L_2 are light outputs from integrating the signal within short and long time intervals

phoswich detectors

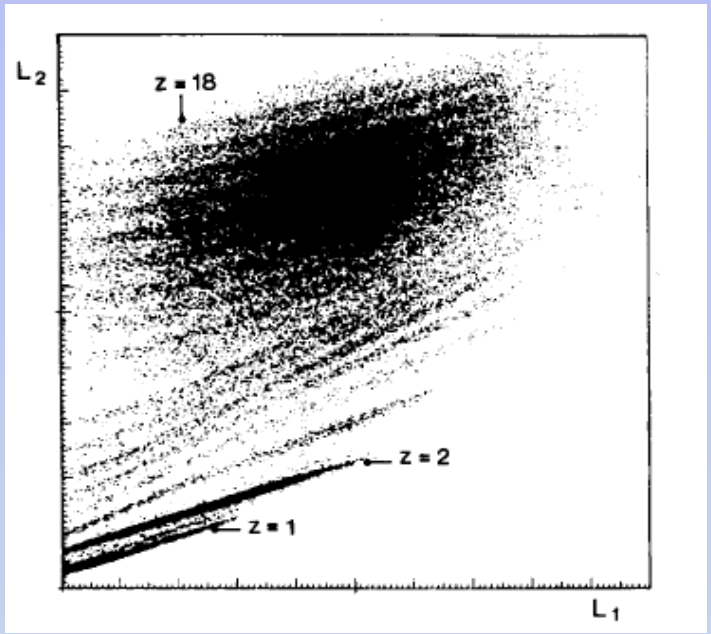


photodetector (PMT, photodiode)

slow crystal

fast crystal (plastic scint.)

L_1, L_2 are light outputs from integrating the signal within short and long time intervals

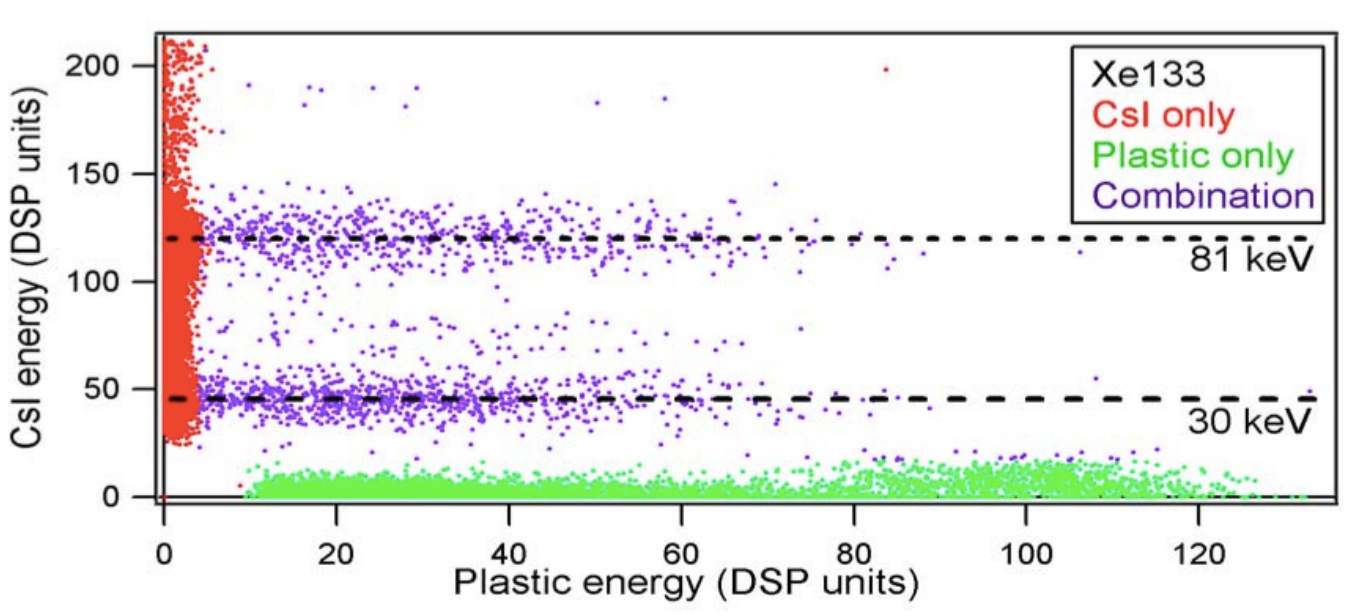


phoswich detectors

The Comprehensive Nuclear-Test-Ban Treaty establishes a network of monitoring stations to detect radioactive xenon in the atmosphere from nuclear weapons testing.

Detect beta-gamma coincidences from the Xe isotope of interest

- CsI(Tl) crystal to measure gamma rays
- Plastic scintillator BC-404 to measure the electrons

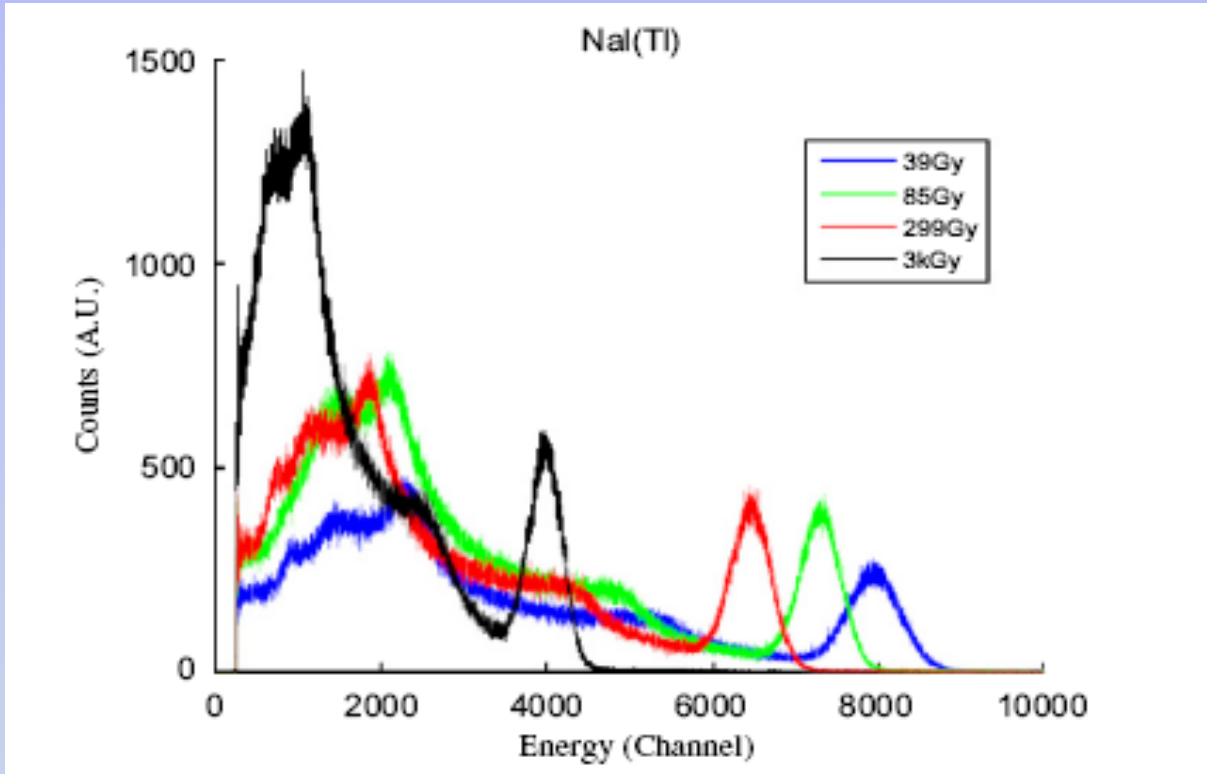


Coincidence events form two horizontal bands, corresponding to 30 keV X-rays or 81 keV gamma rays in coincidence with betas of varying energy

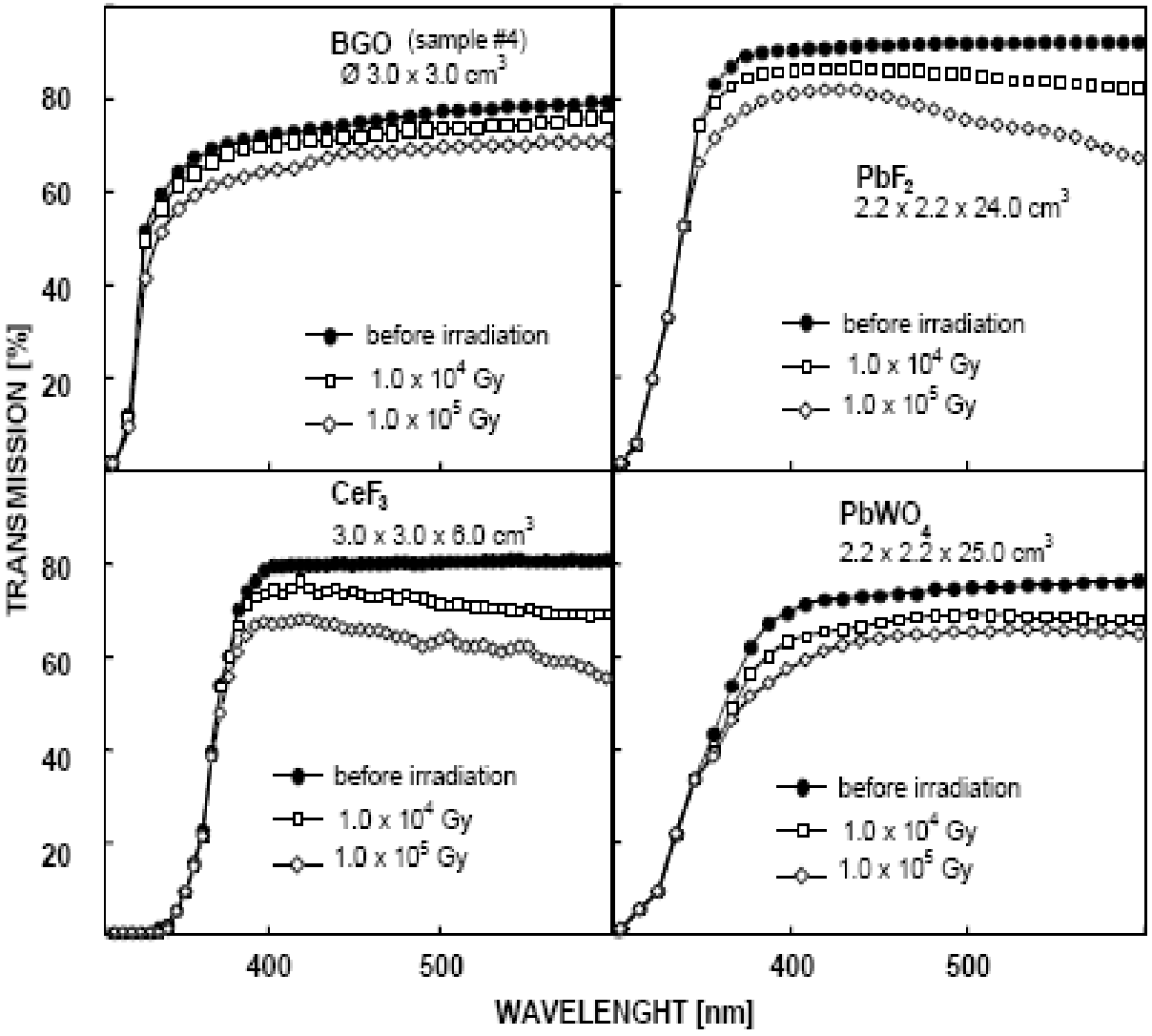
Radiation hardness

Scintillators, like other detector materials, are sensitive to high radiation doses.

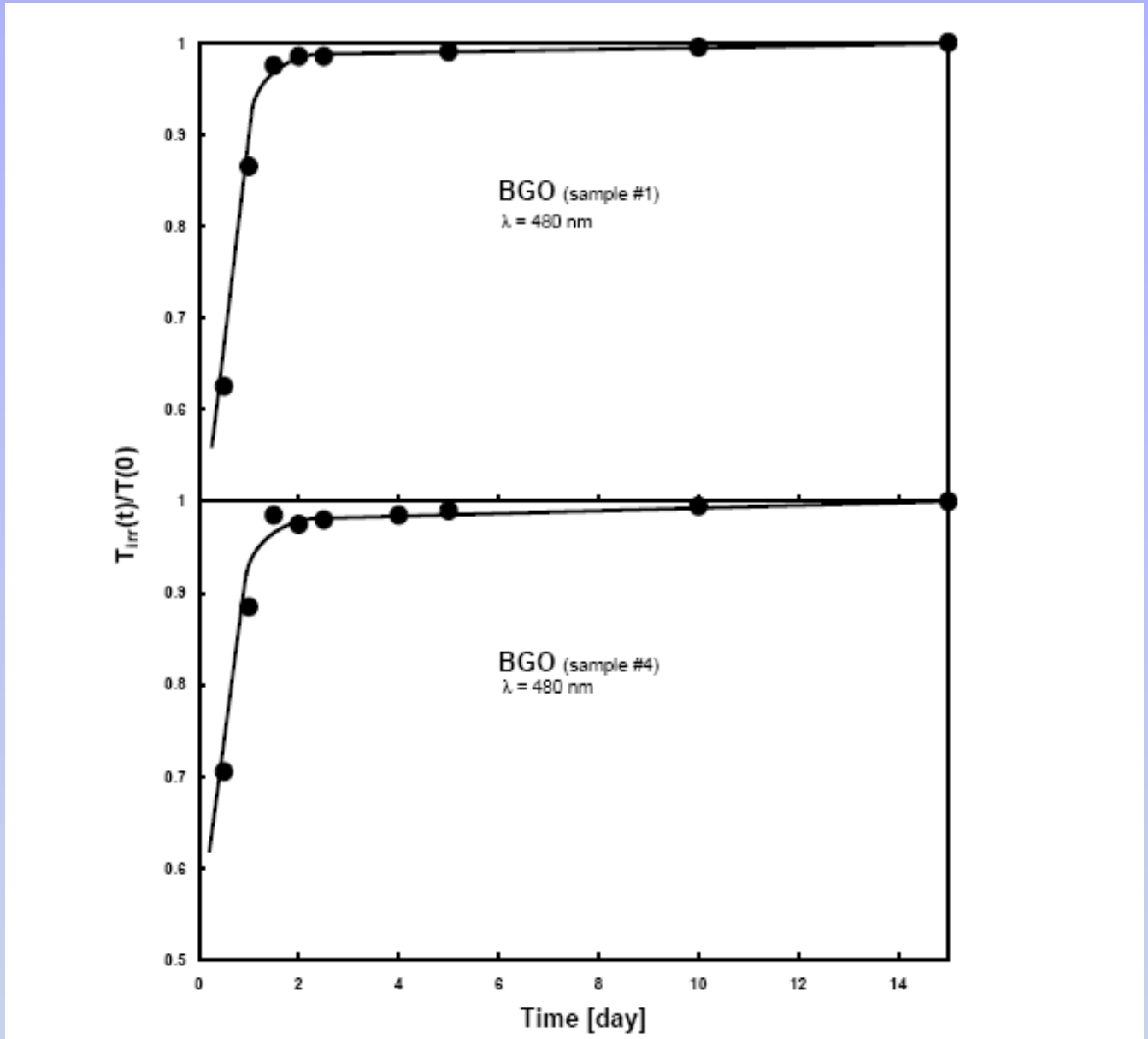
Radiation damage is exhibited in form of lowered light yield and optical transmission.



Optical transmission



Recovery (optical transmission)



Problems

If the energy resolution of a particular NaI(Tl) scintillation detectors is 7% for ^{137}Cs gamma rays (662 keV), estimate its energy resolution for the 1.28 MeV gamma rays of ^{22}Na

Solution:

R=FWHM/Ho with

FWHM: FWHM of the full energy peak

Ho: mean pulse height corresponding to the same peak

Therefore,

$R=K/E^{1/2}$

$K=R_{Cs}E_{Cs}^{0.5}=7\%*662\ keV=5.695$

$R_{Na}=5.695/E_{Na}^{0.5}=5.695/1280^{0.5}=5.03\%$

9.11. A scintillator absorbs an incident flux of 5 MeV alpha particles that totals 10^6 particles/s. The scintillation efficiency for these particles is 3%, and the average wavelength of the emitted light is 420 nm. If the scintillator is coupled to a photodiode with an average quantum efficiency of 75% for the scintillation light and the light collection efficiency is 80%, estimate the expected signal from the photodiode when operated in current mode.

Solution:

$$\text{Energy deposition rate} = (5\times10^6\ \text{eV})(10^6) = 5\times10^{12}\ \text{eV/s}$$

$$\text{Average photon energy} = \frac{1.240\times10^6\ \text{eV}\cdot\text{m}}{420\times10^{-9}\ \text{m}} = 2.95\ \text{eV/ph}$$

$$\text{Photon emission rate} = \frac{5\times10^6\ \text{eV/s}\times0.03}{2.95\ \text{eV/ph}} = 5.08\times10^{10}\ \text{ph/s}$$

$$\therefore\ I = (5.08\times10^{10}\ \text{ph/s})(0.80)(0.75\ e^-/\text{ph})(1.6\times10^{-19}\ \text{C}/e^-)$$
$$= 4.88\times10^{-9}\ \text{C/s}$$
$$= 4.88\ \text{nA}$$

9.8. Calculate the amplitude of the signal pulse expected from a NaI(Tl)–PM tube combination under the following circumstances:

Radiation energy loss: 1.2 MeV.

Light collection efficiency: 70%.

Photocathode quantum efficiency: 20%.

PM tube electron gain: 100,000.

Anode capacitance: 100 pF.

Anode load resistance: 10^5 ohms.

Any other physical parameters you may need can be found in the text.

Solution:

$RC = (10^5\Omega)(10^{-10}\ F) = 10^{-5}\ s$

τ for NaI(Tl) $= 230 \times 10^{-9}\ s$

Since $RC >> \tau$, the maximum pulse height $V = Q/C$

$n = E \cdot \varepsilon_{scint}/h\nu = (1.2\times10^6\ eV)(0.12)/(3\ eV/photon) = 4.8\times10^4$ photons

$Q = n$(light coll. eff.)(photo cath. eff.)(1^{st} dynode eff.)(gain)q_e

$= (4.8\times10^4)(0.7)(0.2)(0.8)(100{,}000)(1.62\times10^{-19}\ C) = 8.71\times10^{-11}\ C$

max. pulse height $= Q/C = (8.71\times10^{-11}\ C)/(10^{-10}\ F) = 0.871\ V$