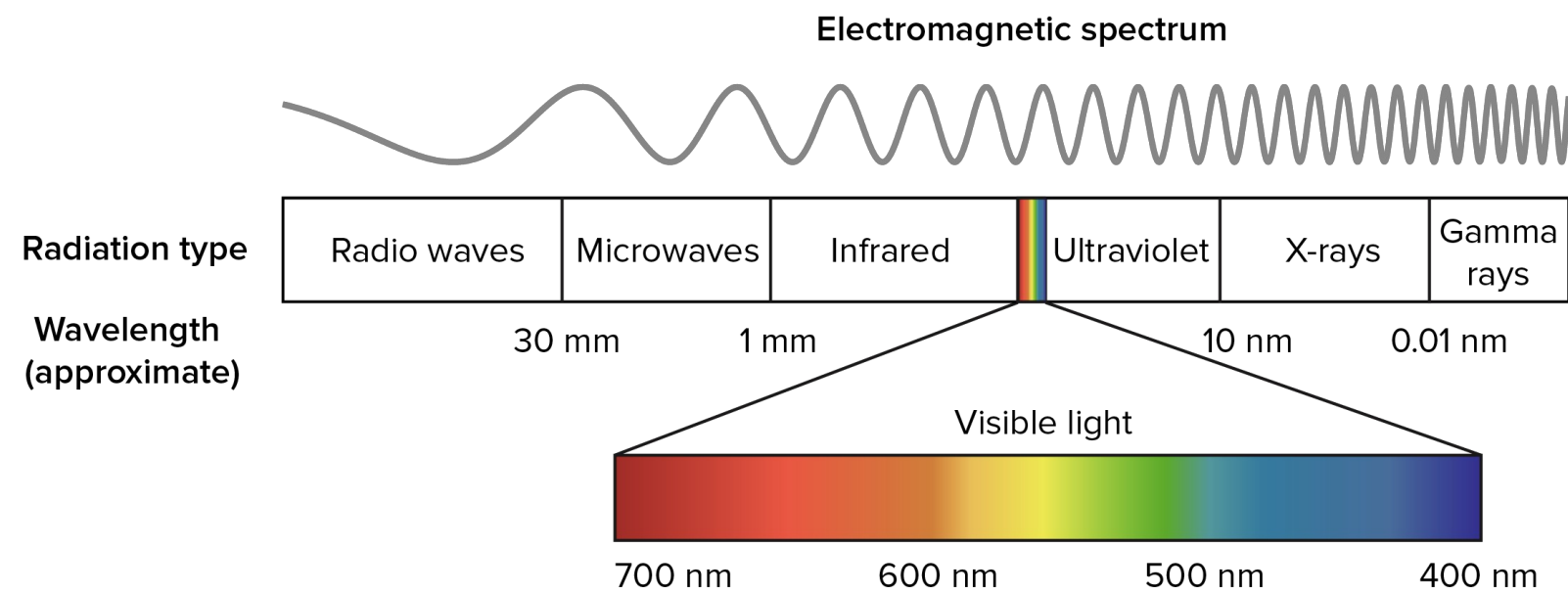


Lecture: Scintillation Detectors

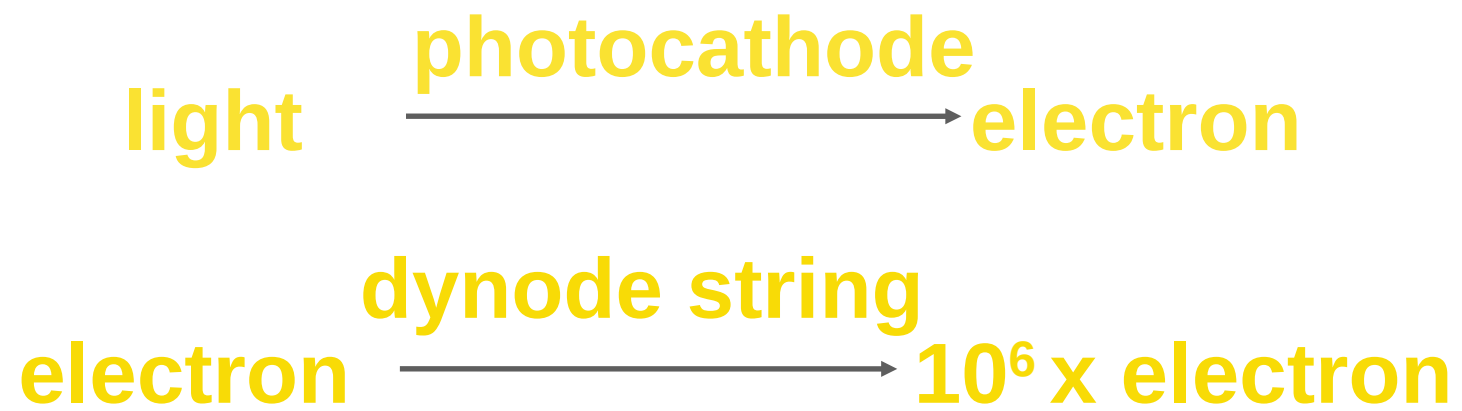
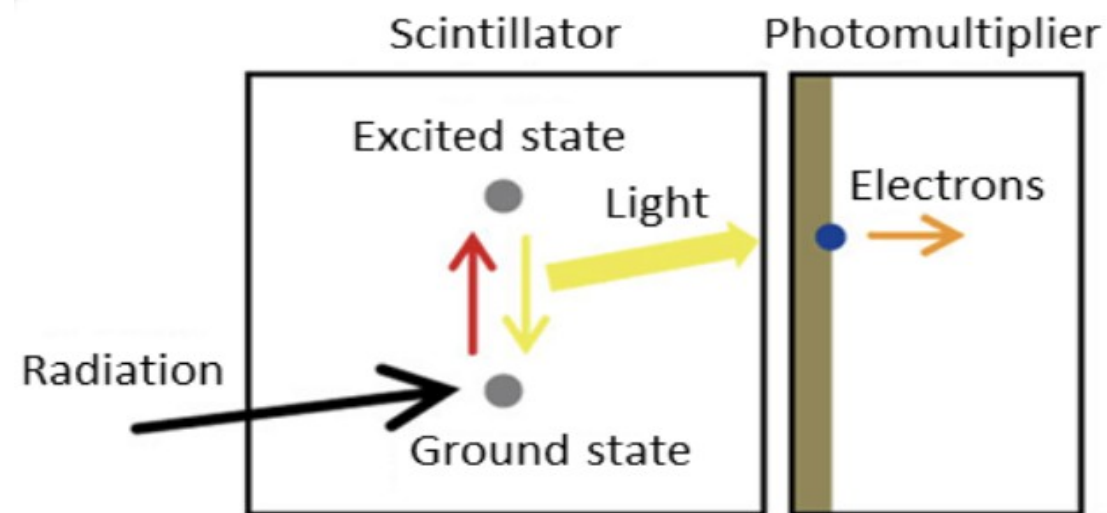
**Chapters 7, 8.1, 8.2, 8.5, 8.6, 8.7
except 7.4 and 7.5,
(8.8, 8.9 and 9.7 are optional)**





Wavelength is one of the characteristics we know about each scintillation material.

Scintillation mechanism:



Organic scintillators

Low-Z materials

Fast response time

High hydrogen content

Best for β particles and fast neutrons

Inorganic scintillators

High-Z materials

Dense

Slow response time

Best for γ rays

Note that heavy charged particles like protons, alpha particles, heavier mass nuclei.. We don't use scintillation detectors for their effective detection.

We use mainly gas detectors and Silicon semiconductor detectors.

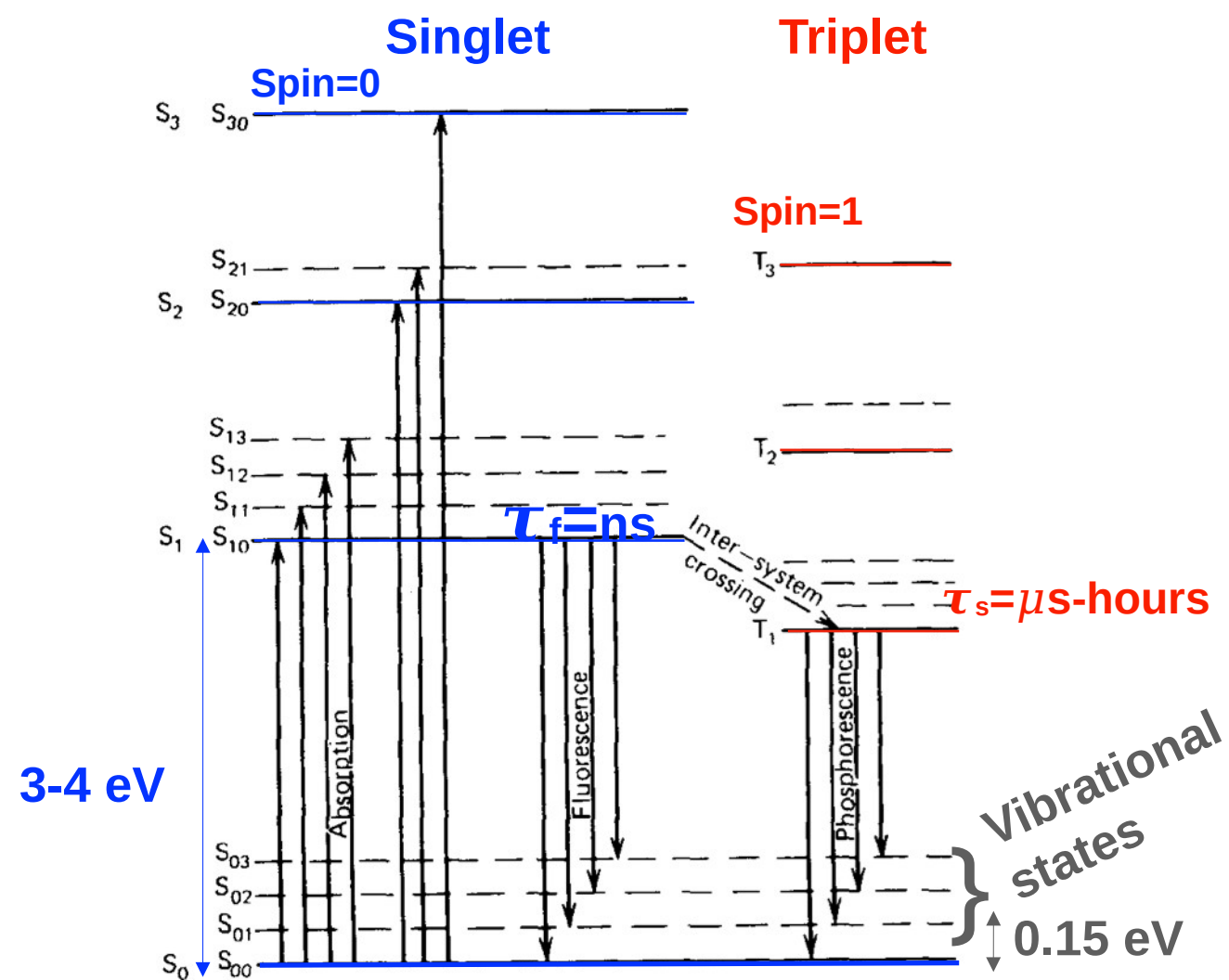
Today

- Scintillation
 - Organic scintillators
 - Anthracene
 - Stilbene
 - Plastic
 - Liquid
 - Inorganic scintillators
 - NaI(Tl)
 - CsI(Tl)
 - LaBr₃(Ce)
 - BGO
- PMTs (Photomultiplier Tubes)
 - Mechanism
 - Photocathode
 - Quantum efficiency
- Time response
 - Organic
 - Inorganic
- Pulse shape discrimination
 - Organic
- Light output
 - Organic
 - Inorganic
- Energy resolution
 - Inorganic
- Detector efficiency
 - Heavy charged particle
 - Electrons
 - Gamma rays
 - Neutrons

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- Scintillation
 - Organic scintillators
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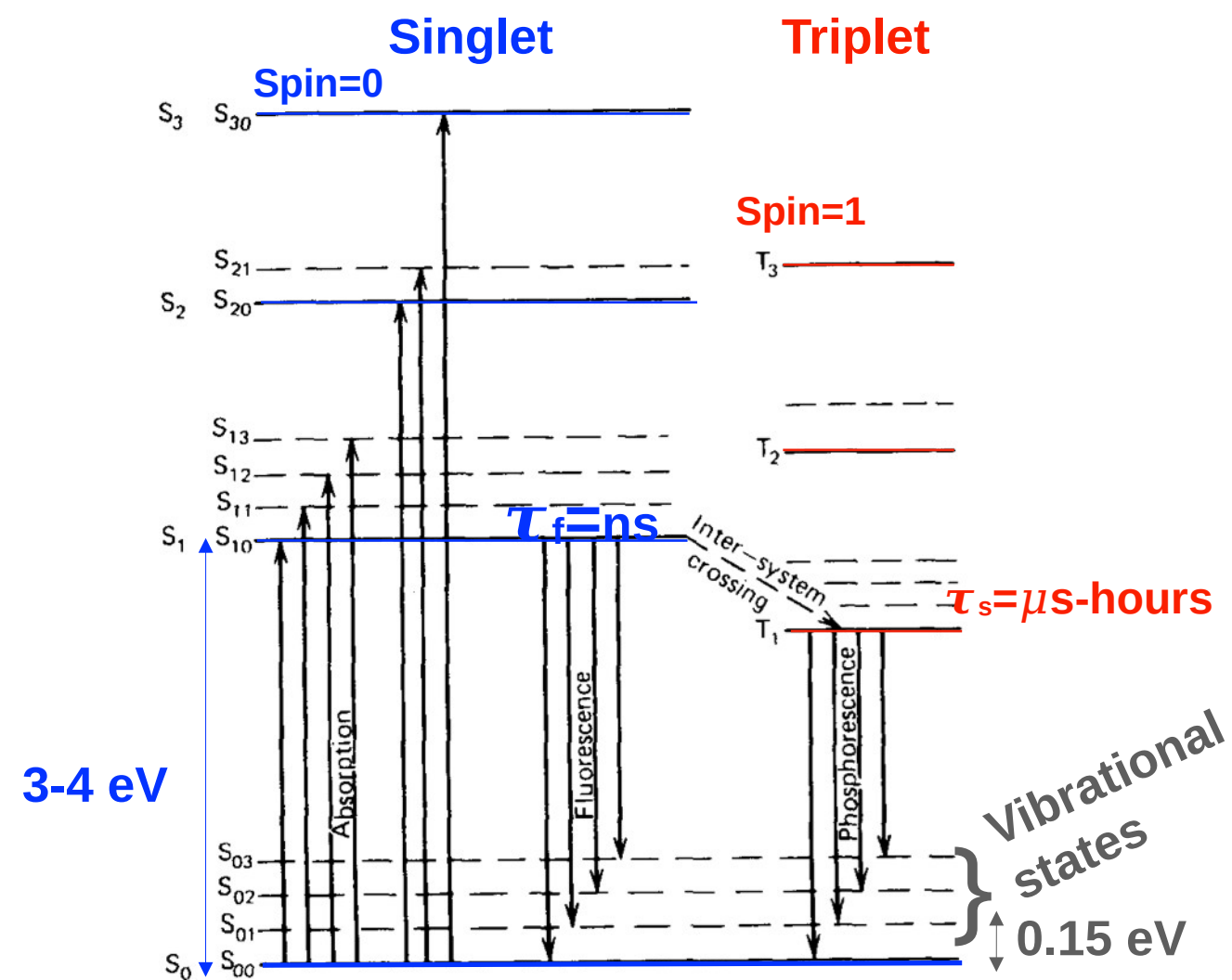
electronic structure of a molecule



Thermal energy: 0.025 eV
In room temperature almost all molecules are in S_{00}

Singlet states: States with shorter lifetimes
Triplet states :Meta-stable states

electronic structure of a molecule



Fluorescence

Phosphorescence

Quenching

Singlet states: States with shorter lifetimes

Triplet states :Meta-stable states

organic crystal scintillators

Highest light output
Fragile

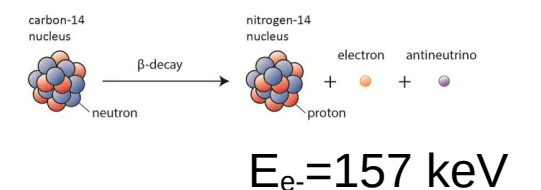
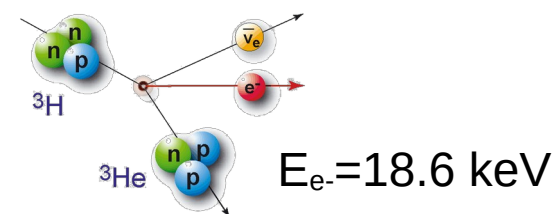


Low light output/fragile
Best separation between
charged particles and electrons



Can be used in large volumes
not fragile=flexible

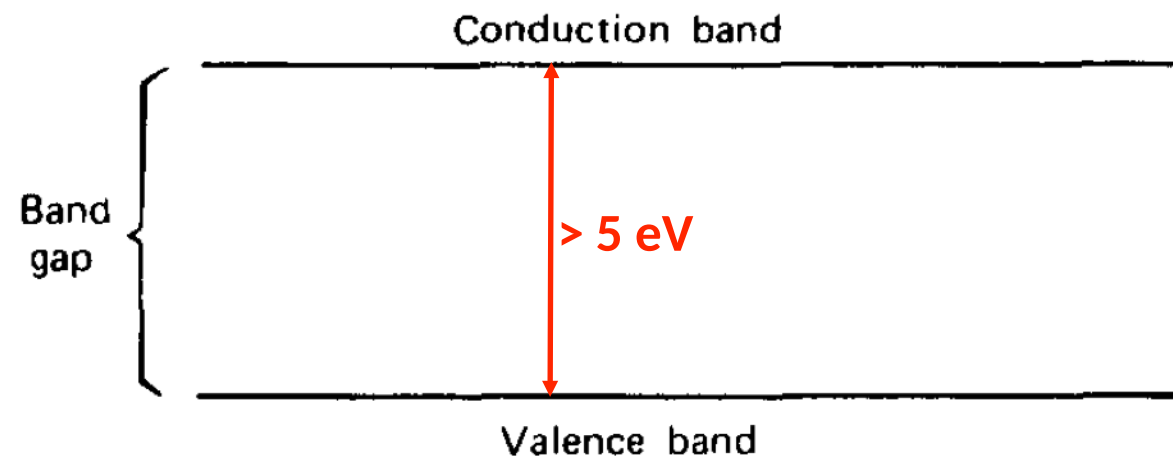
Low radiation damage
Good for tritium and ¹⁴C in low-level β activity



Today

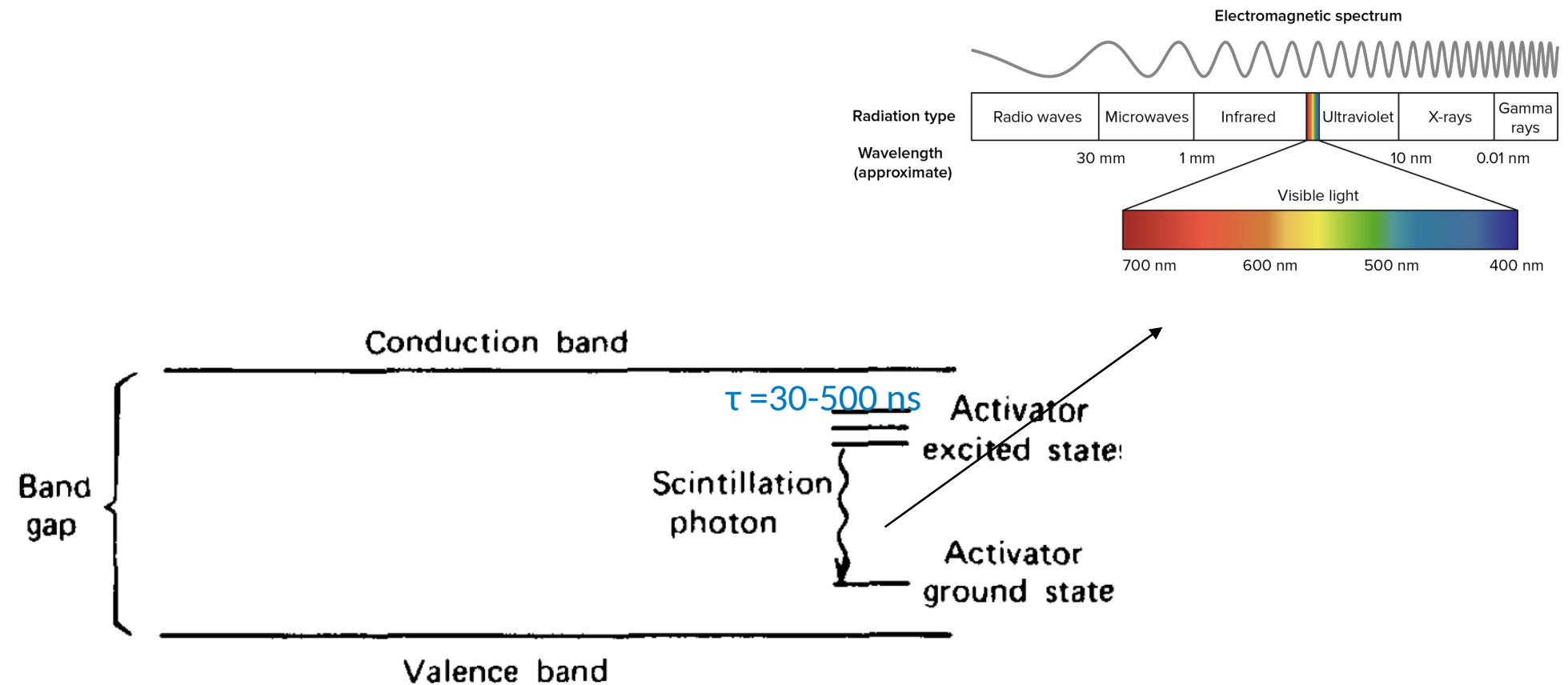
- Scintillation
 - Organic scintillators
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 - Gamma rays
 - Neutrons

pure NaI



- 0 Inorganic scintillators are **insulators** where the forbidden band gap is larger than 5 eV
- 0 Photons will not be emitted in the visible light range.

NaI (Tl)



- We add impurity or so-called activator.
- Very little amount is sufficient: *Tl* in NaI is 0.1% of total NaI concentration.
- Activator state's decay time is long: 30-500 ns.
- This is the time which determines the decay time of the inorganic crystals.

- Inorganic crystals are slower due to phosphorescence, i.e., slow timing response
- Longer decay time $\tau \sim 500 \text{ ns}$
- But high density and stopping power thus high efficiency --> gamma rays
- Highest light output, better energy resolution (compared to organic scintillators)
- A major disadvantage of certain inorganic crystals is **hygroscopicity**. NaI, in particular, is a prime example.

They get water molecules attached easily from the moisture in air. They are thus put into a protective airtight housing.

Photoelectric absorption cross section

$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

$n=4 \text{ or } 5$

NaI(Tl):
 Na (Z=11) } $Z_{\text{eff}}: 50.8$
 I (Z=53)

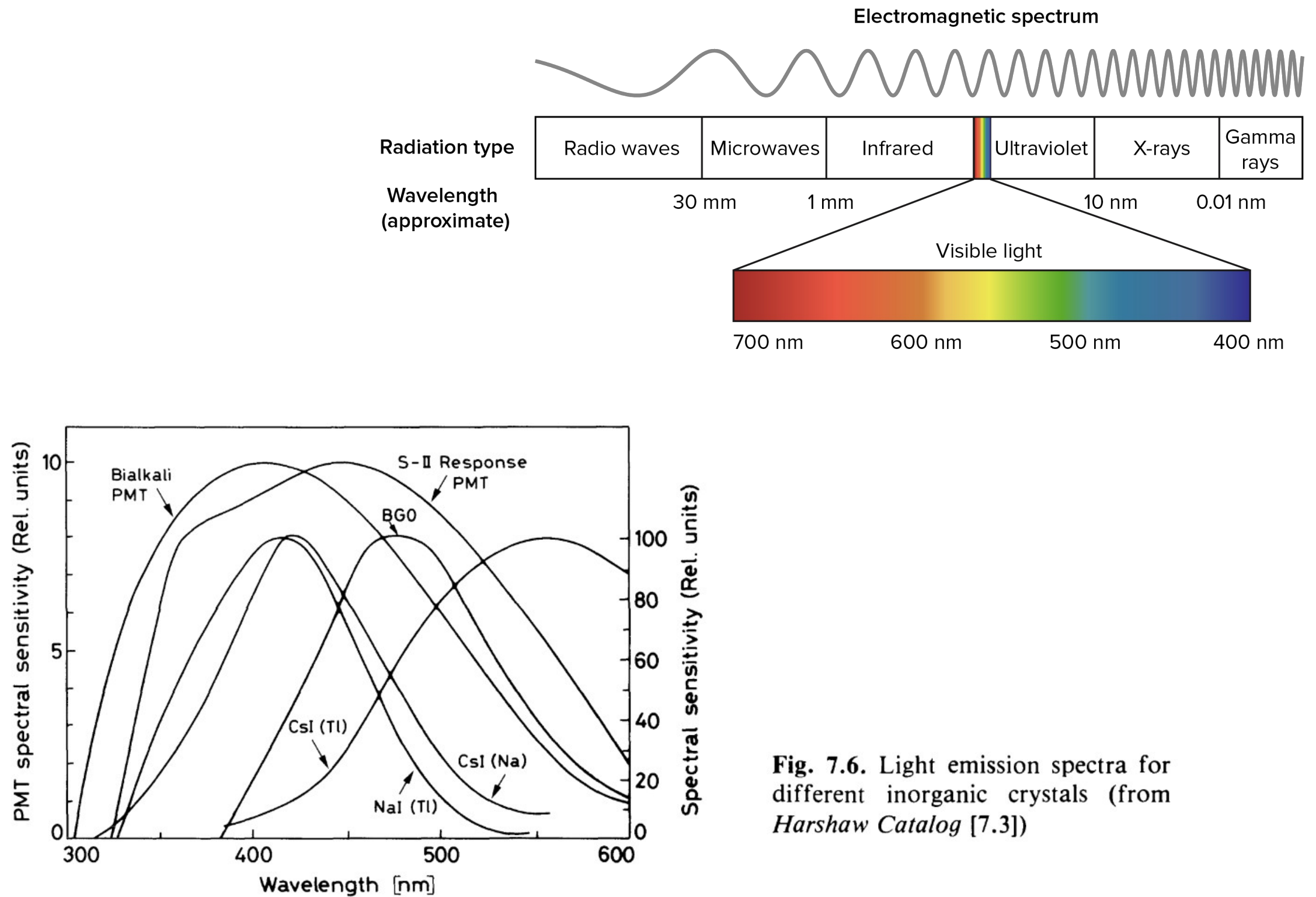
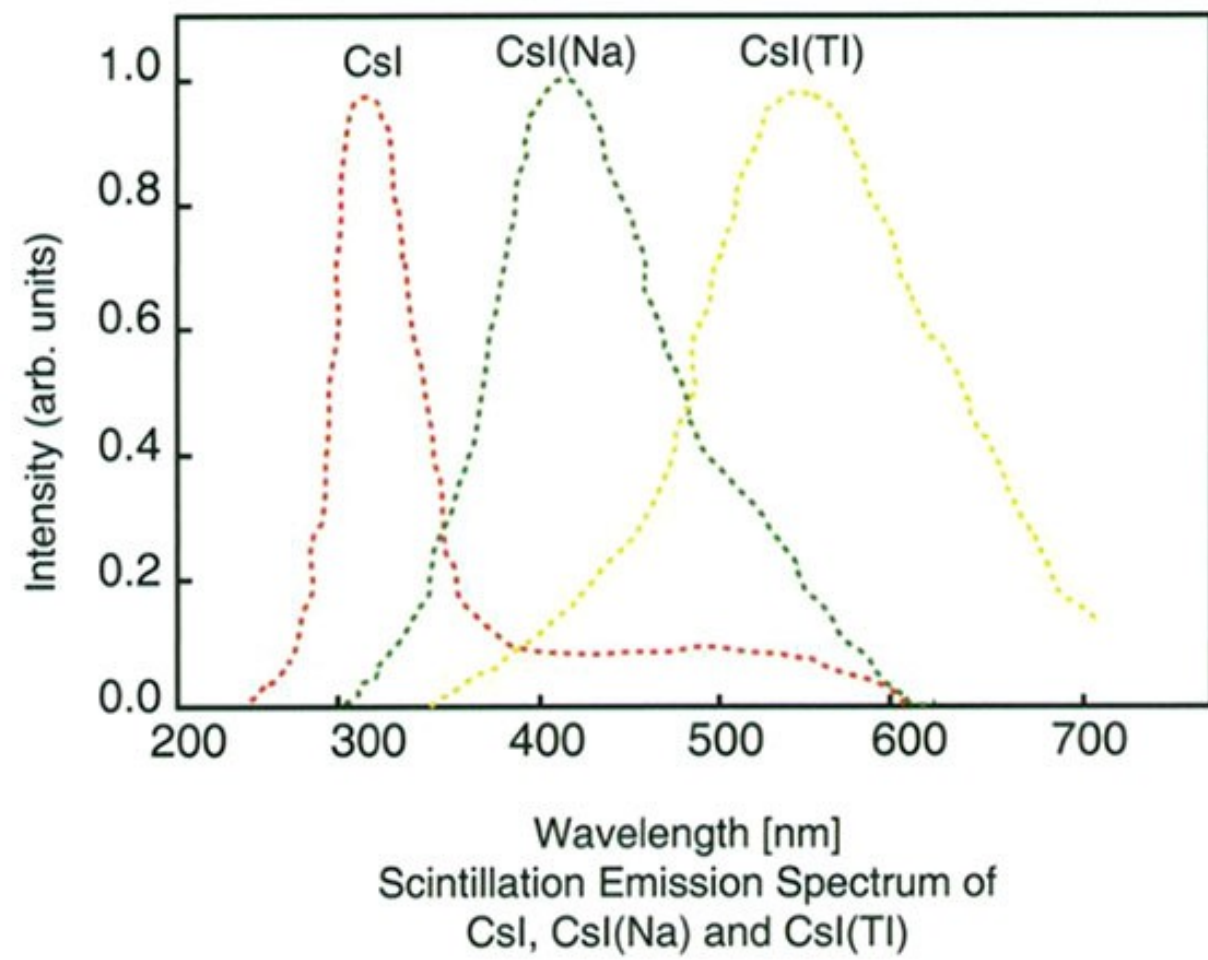
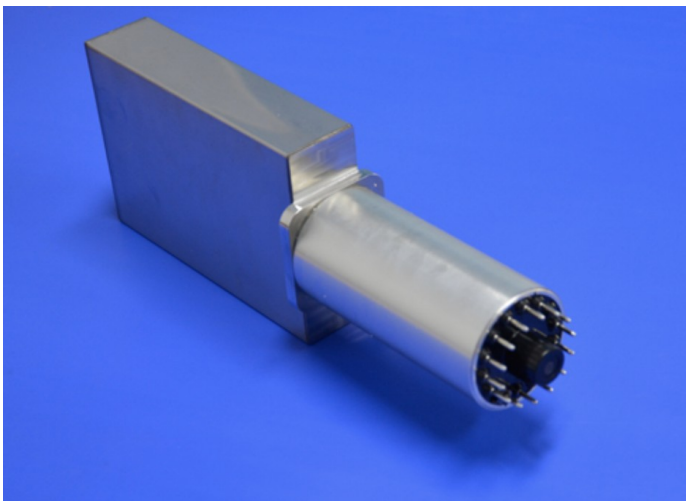
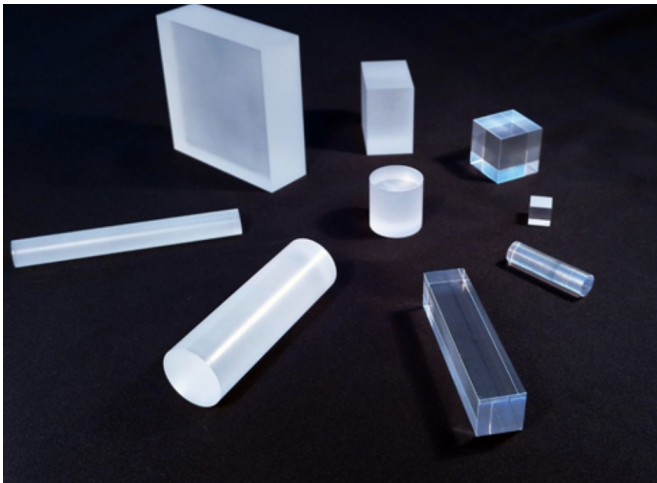


Fig. 7.6. Light emission spectra for different inorganic crystals (from *Harshaw Catalog* [7.3])

NaI (TI)



CsI (TI)



Lanthanum Bromide Scintillation Radiation Detectors

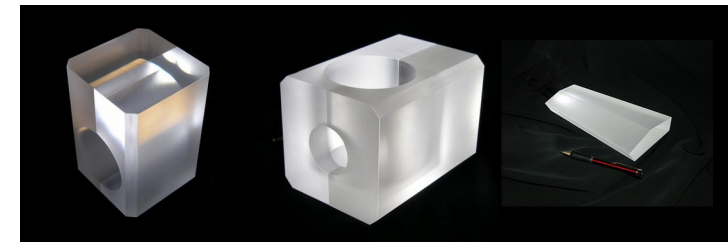
- High light output, and fast decay time output pulse.
- Better energy resolution and stability than NaI(Tl).
- Higher maximum throughput at high input count rates.

Lanthanum Bromide, or $\text{LaBr}_3(\text{Ce})$, is one of the new generation of inorganic scintillation gamma-ray detectors. LaBr detectors exhibit improved resolution and faster light decay time.



When used with the latest ORTEC digital electronics, these detectors provide improved resolution, pulse shape, and temperature stability compared to NaI(Tl) types.

BGO ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$)



High Z ($Z=83$), high density ($d=7.13$ g/cm³) scintillation material.

Only inorganic scintillator without activator

BGO is a very **efficient gamma ray absorber**.

High Z values cause large the **photo-fraction** for gamma ray absorption
very **good peak-to-total** ratios are observed.

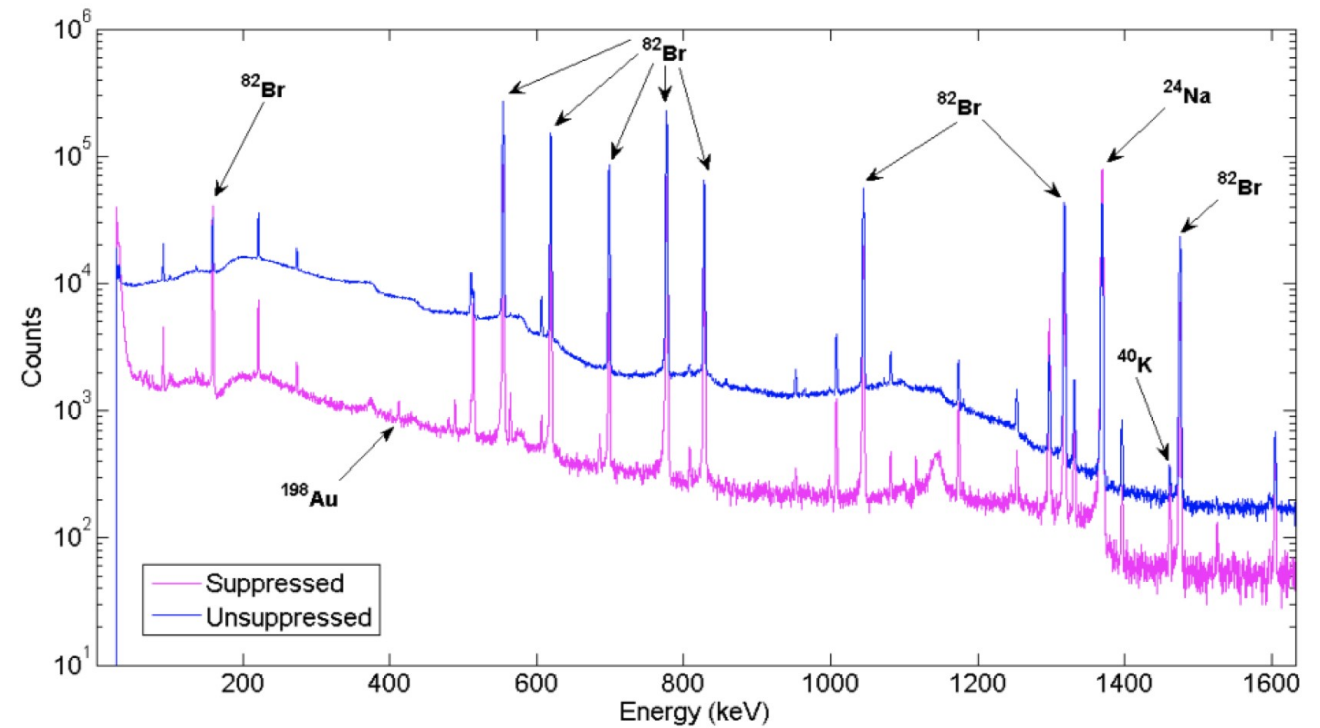
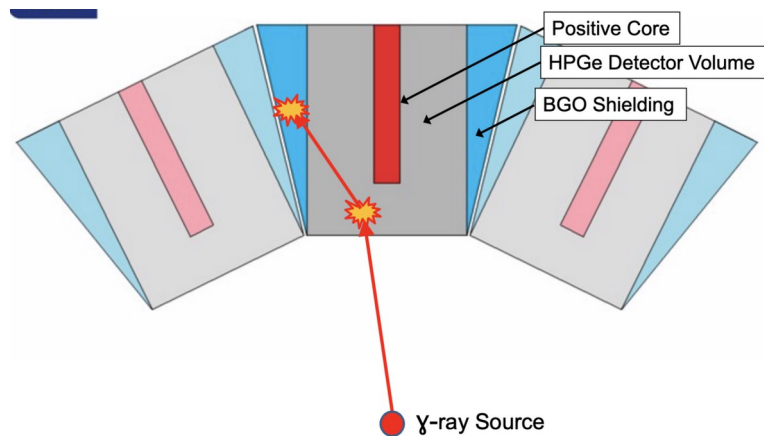
$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

$n=4$ or 5

Poor resolution. Why?? We will see it soon.

BGO ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$)

Compton Suppression Anti Compton Shields Calorimeter



[https://www.rsec.psu.edu/assets/PDF/8-RSECBook_Compton Suppression.pdf](https://www.rsec.psu.edu/assets/PDF/8-RSECBook_Compton%20Suppression.pdf)



Scintillation properties of inorganic materials

TABLE 6.1
Properties of Certain Inorganic Scintillators

Material	Wavelength of Maximum Emission (nm)	Scintillation Efficiency (Relative, %)	Decay Time (μ s)	Density (10^3 kg/m^3)
NaI(Tl)	410	100	0.23	3.67
CaF ₂ (Eu)	435	50	0.94	3.18
CsI(Na)	420	80	0.63	4.51
CsI(Tl)	565	45	1.00	4.51
Bi ₄ Ge ₃ O ₁₂	480	8	0.30	7.13
CdWO ₄	530	20	0.90	7.90
⁶ LiI(Eu)	470	30	0.94	3.49

Scintillation properties of organic materials

TABLE 6.3
Properties of Certain Organic Scintillators

Material	Wavelength of Maximum Emission (nm)	Relative Scintillation Efficiency (%)	Decay Time (ns)	Density (10^3 kg/m^3)
Anthracene	445	100	~30	1.25
<i>trans</i> -Stilbene	385	~60	4–8	1.16
NE 102	350–450	~65	2	1.06
NE 110	350–450	60	3	1.06
NE 213 (liquid)	350–450	~60	2	0.867
PILOT B	350–450	68	2	1.06
PILOT Y	350–450	64	~3	1.06

Detector Type	Resolution @622 keV (%)	Density (g/cc)	Photoelectron Yield Relative to NaI	Primary Decay Time (usec)
LaBR ₃ (Ce)	2.8 - 4.0	5.29	130	0.026
NaI(Tl)	7	3.7	100	0.230

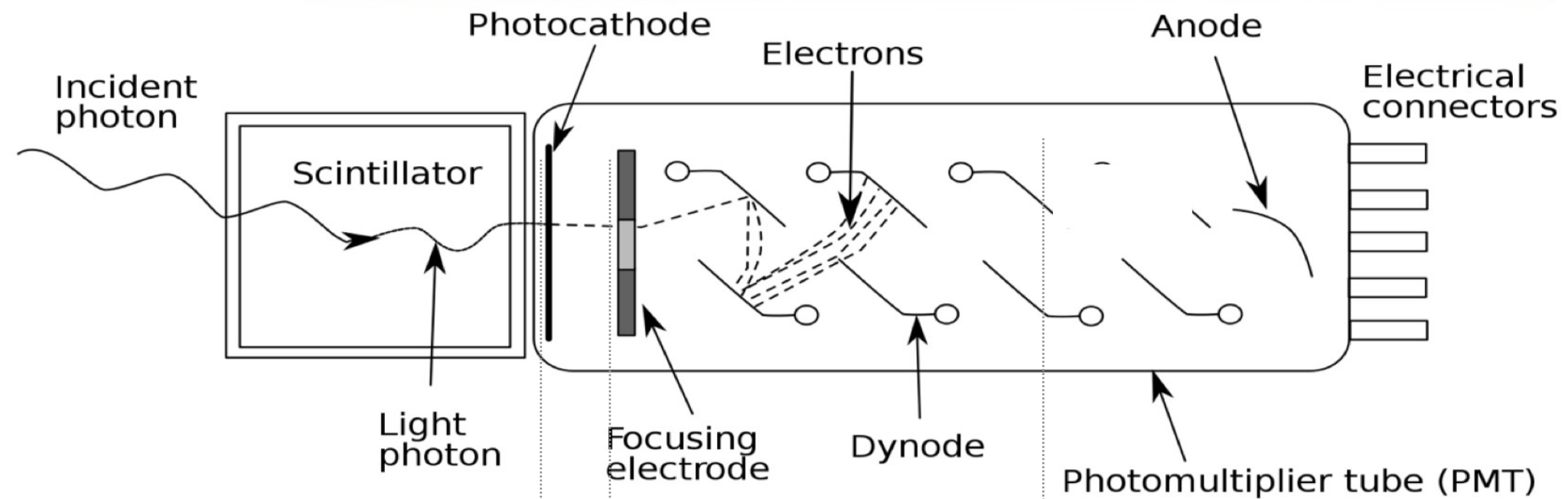
Today

- Scintillation
 - Organic scintillators
 - Anthracene
 - Stilbene
 - Plastic
 - Liquid
 - Inorganic scintillators
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 - CsI(Tl)
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- Light output
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 - Inorganic
- Energy resolution
 - Inorganic
- Detector efficiency
 - Heavy charged particle
 - Electrons
 - Gamma rays
 - Neutrons

Photo multiplier tubes (PMTs)

- Scintillation material (organic and inorganic) will not work as a detector without a PMT tube
- Photocathode before PMT
- Anode after PMT

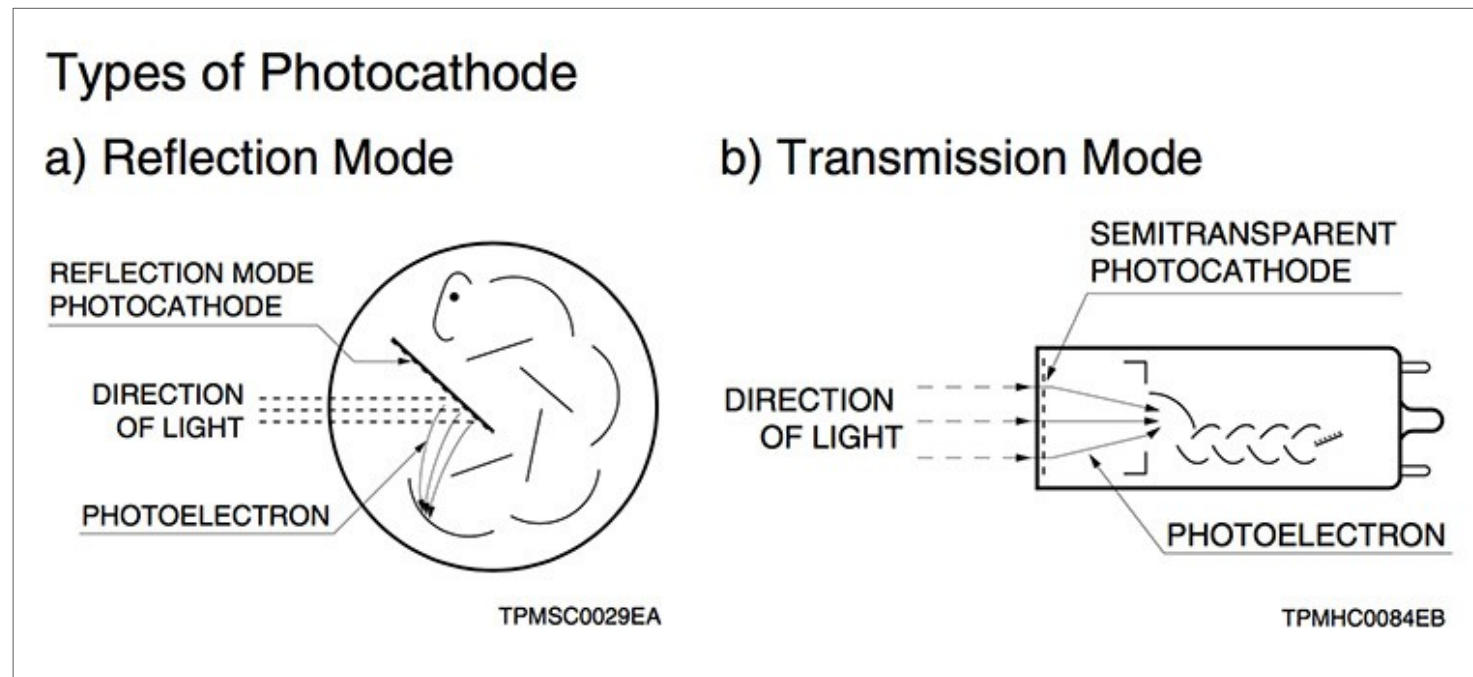
- I) Light (photon) creation
- II) Photoelectron creation
- III) Electron multiplication
- IV) Electron collection on Anode



25

(I) (II) (III) (IV)

Photocathode



<https://www.hamamatsu.com/jp/en/support/glossary/p.htm>
!

not all photoelectrons will escape!! ~20-30% eff.

Photocathode Quantum efficiency: 20-30% in NaI(Tl)

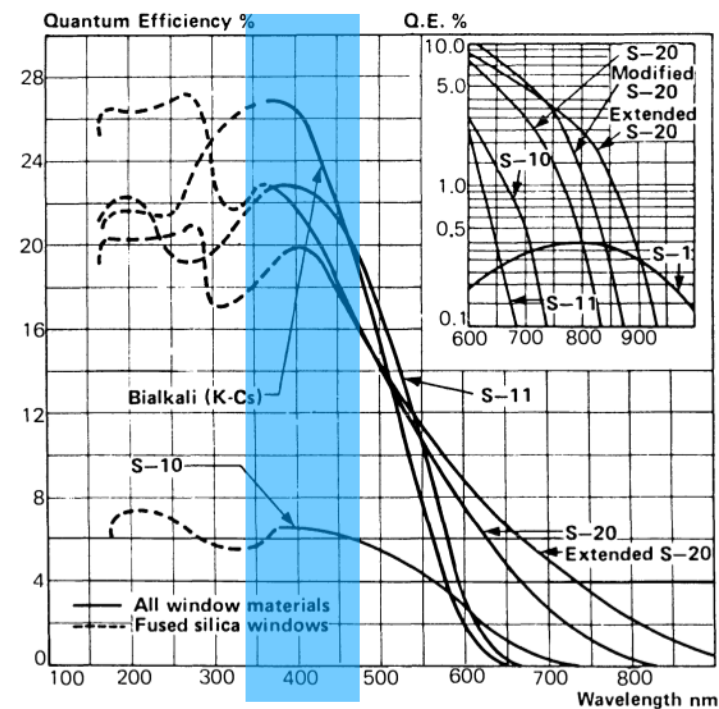


Table 8.1. Photocathode characteristics (from RTC catalog [8.3])

Cathode type	Composition	λ at peak response [nm]	Quantum efficiency at peak
S1 (C)	Ag-O-Cs	800	0.36
S4	SbCs	400	16
S11 (A)	SbCs	440	17
Super A	SbCs	440	22
S13 (U)	SbCs	440	17
S20 (T)	SbNa-KCs	420	20
S20R	SbNa-KCs	550	8
TU	SbNa-KCs	420	20
Bialkali	SbRb-Cs	420	26
Bialkali D	Sb-K-Cs	400	26
Bialkali DU	Sb-K-Cs	400	26
SB	Cs-Te	235	10

Most of the Photocathodes used today are **semiconductor** materials where the QE is changing between 10 to 30%.

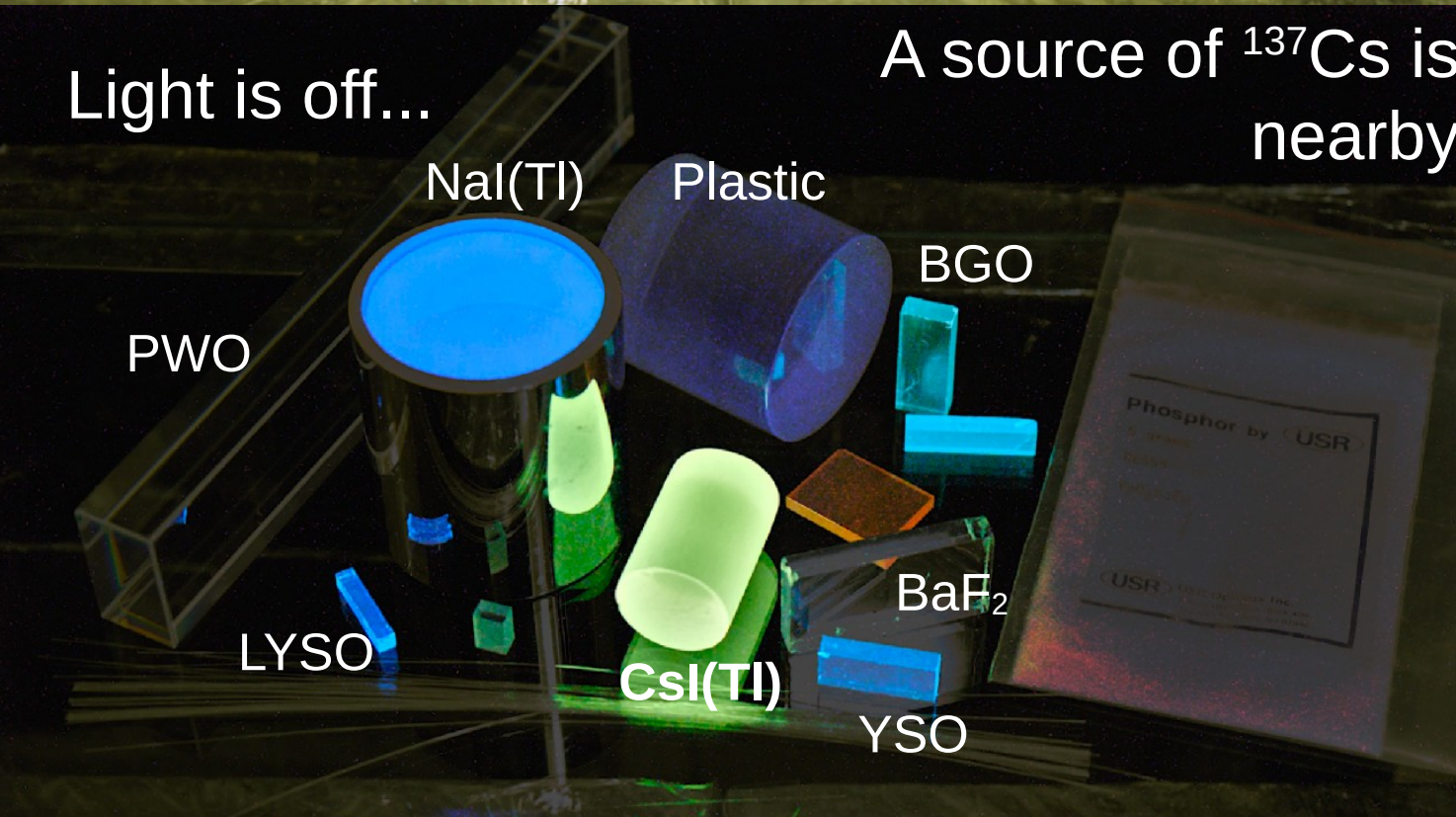
Photocathodes in **metal** form have very low QE around 0.1%! **Why?**

Lights on...



Light is off...

A source of ^{137}Cs is nearby



NaI (TI)

NP & HEP

CsI(TI)

BaF₂ : Barium fluoride

Plastic

BGO: Bismuth Germanate (B₄Ge₃O₁₂)

YSO :Yttrium Silicon Oxide (Y₂SiO₅:Ce)

PET

LYSO: Lutetium Yttrium Silicon Oxide

Lu_{1.8}Y_{0.2}SiO₅:Ce)

PWO: Lead Tungstate (PbWO₄)

HEP (CERN)

Properties	BGO	LYSO
Density (g/m ³)	7.13	7.3
Melting Point (°C)	1050	2047
Index of Refraction	2.15	1.82
Radiation Length (cm)	1.10	1.16
Attenuation (cm-1)	0.96	0.87
Decay Constant (ns)	300	50
Light Yield (%) NaI (TI)	25	75
Photofraction (%)	40	30
Energy Resolution (511 kev,%)	16	20
Radioactivity	No	Yes

Youtube video:

<https://www.youtube.com/watch?v=Gza6Cc8XOCA&t=537s>

Today

- Scintillation
 - Organic scintillators
 - Anthracene
 - Stilbene
 - Plastic
 - Liquid
 - Inorganic scintillators
 - NaI(Tl)
 - CsI(Tl)
 - LaBr₃(Ce)
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 - Organic
- Light output
 - Organic
 - Inorganic
- Energy resolution
 - Inorganic
- Detector efficiency
 - Heavy charged particle
 - Electrons
 - Gamma rays
 - Neutrons

organic scintillators

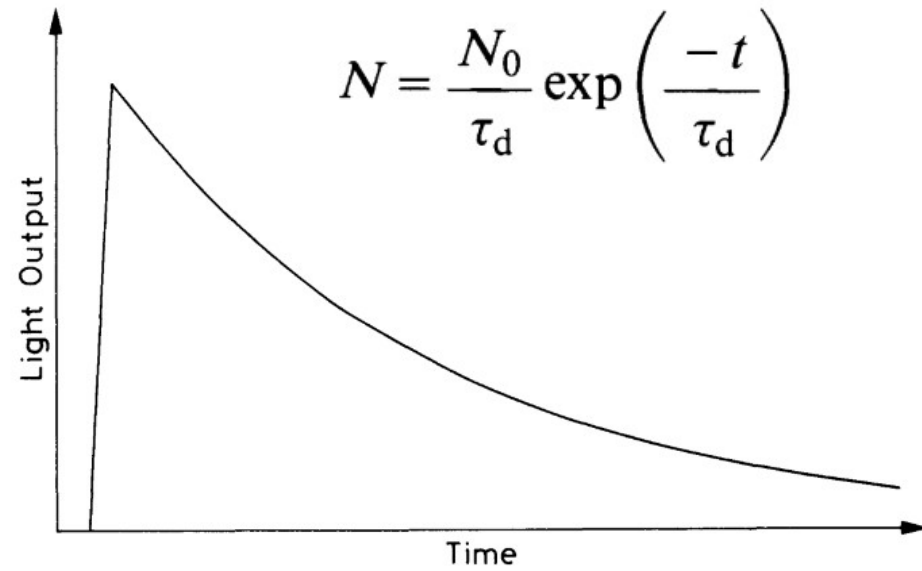


Fig. 7.2. Simple exponential decay of fluorescent radiation. The rise time is usually much faster than the decay time

Decay from the optical levels

- Fast component
- Slow component

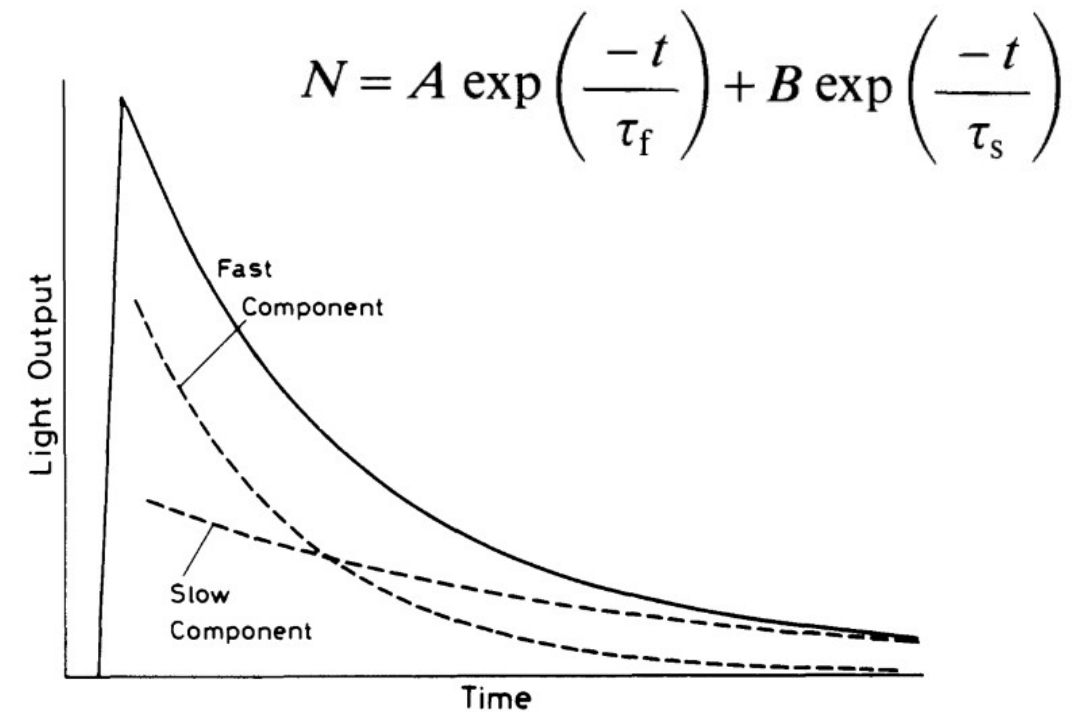


Fig. 7.3. Resolving scintillation light into *fast* (prompt) and *slow* (delayed) components. The *solid line* represents the total light decay curve

organic scintillators

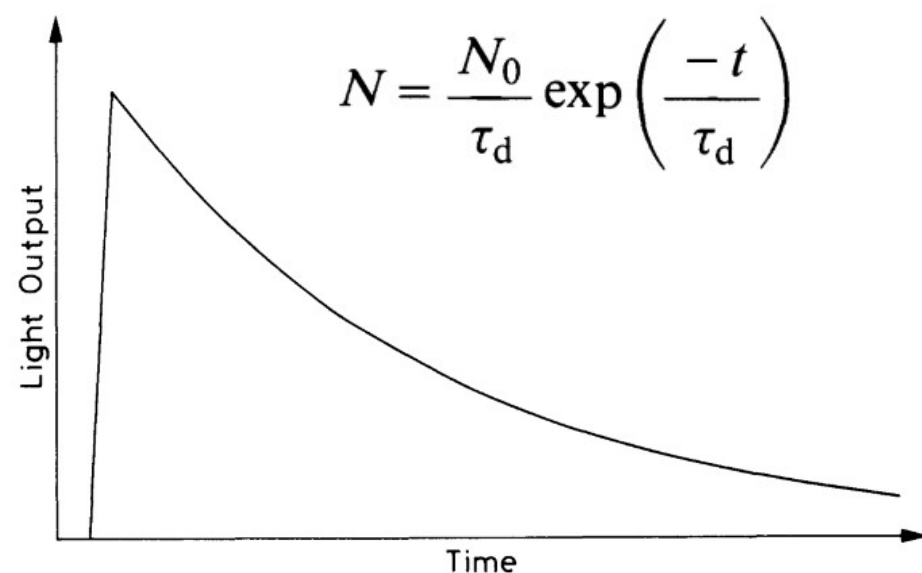


Fig. 7.2. Simple exponential decay of fluorescent radiation. The rise time is usually much faster than the decay time

Decay from the optical levels

- Fast component
- Slow component

Population of the optical levels, i.e. Excitation
Rise time

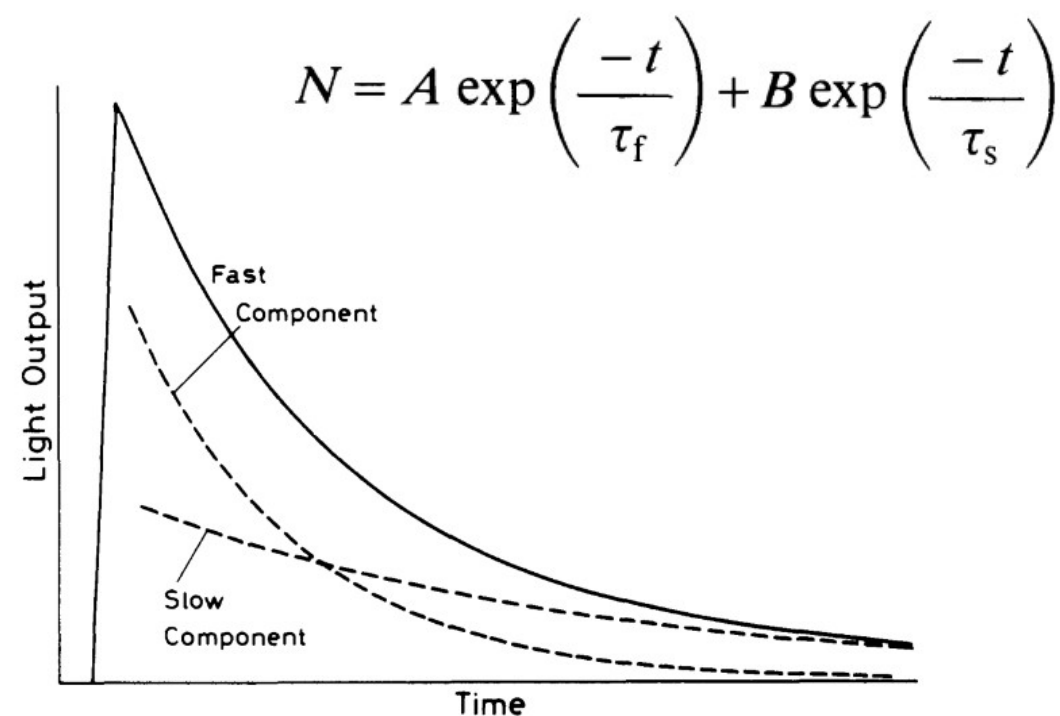


Fig. 7.3. Resolving scintillation light into *fast* (prompt) and *slow* (delayed) components. The *solid line* represents the total light decay curve

$$N(t) = N_0 f(\sigma, t) \exp\left(\frac{-t}{\tau}\right)$$

Table 7.2. Gaussian and exponential parameters for light pulse description from several plastic scintillators (from *Bengston and Moszynski* [7.2])

Scintillator	σ [ns]	τ [ns]
NE102A	0.7	2.4
NE111	0.2	1.7
Naton 136	0.5	1.87

organic scintillators

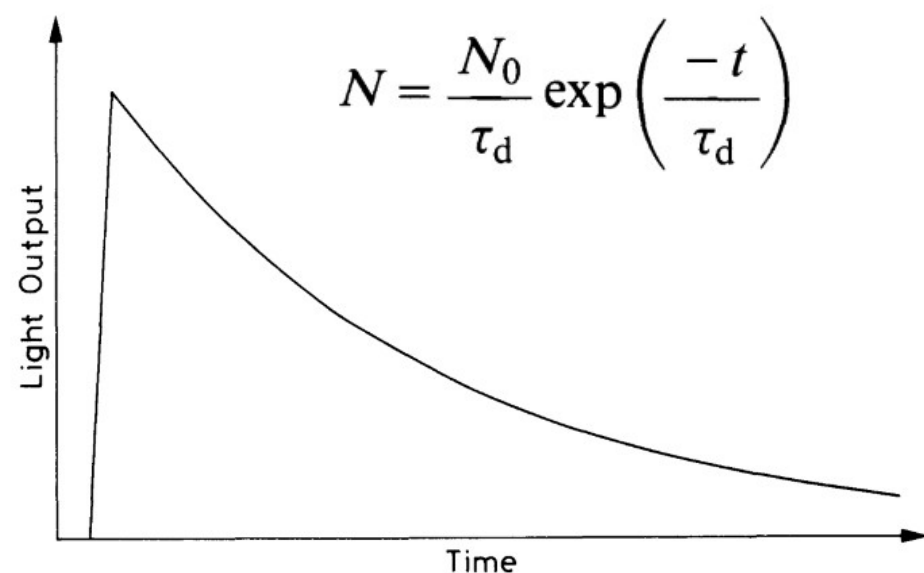


Fig. 7.2. Simple exponential decay of fluorescent radiation. The rise time is usually much faster than the decay time

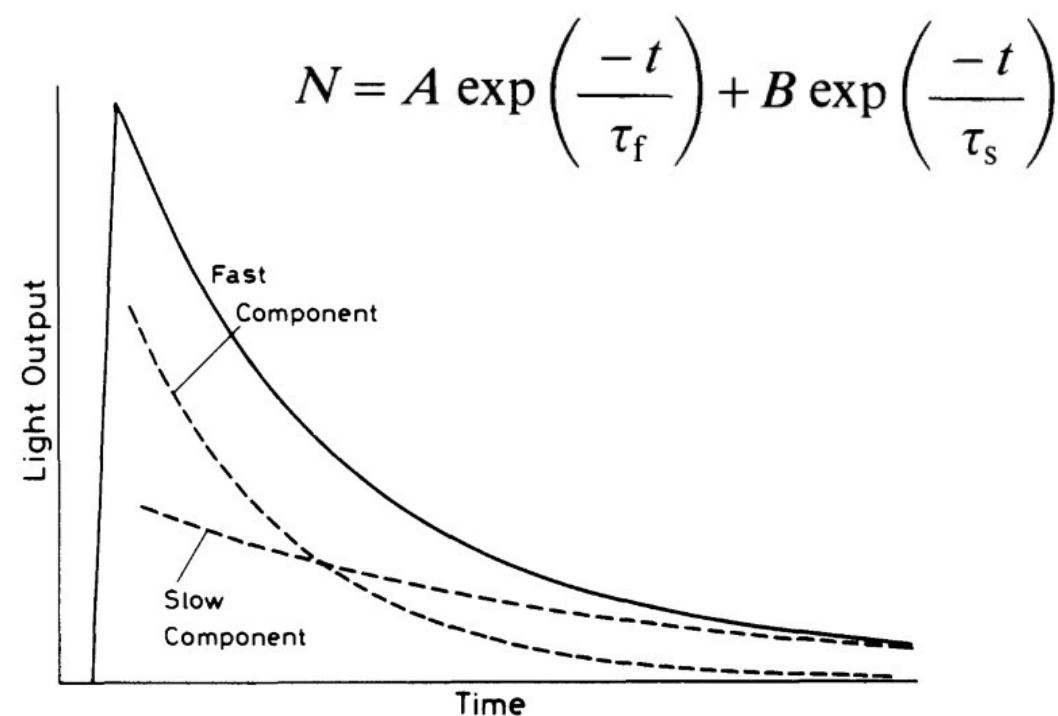


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Decay from the optical levels

- Fast component
- Slow component

Population of the optical levels, i.e. Excitation
Rise time

$$N(t) = N_0 f(\sigma, t) \exp\left(\frac{-t}{\tau}\right)$$

Table 8.2 Some Timing Properties of Fast Plastic Scintillators

	Parameters for Eq. (8.10)		Parameters for Eq. (8.11)		Measured FWHM
	τ_1 (rise)	τ (decay)	σ_{ET}	τ	
NE 111	0.2 ns	1.7 ns	0.2 ns	1.7 ns	1.54 ns
Naton 136	0.4 ns	1.6 ns	0.5 ns	1.87 ns	2.3 ns
NE 102A	0.6 ns	2.4 ns	0.7 ns	2.4 ns	3.3 ns

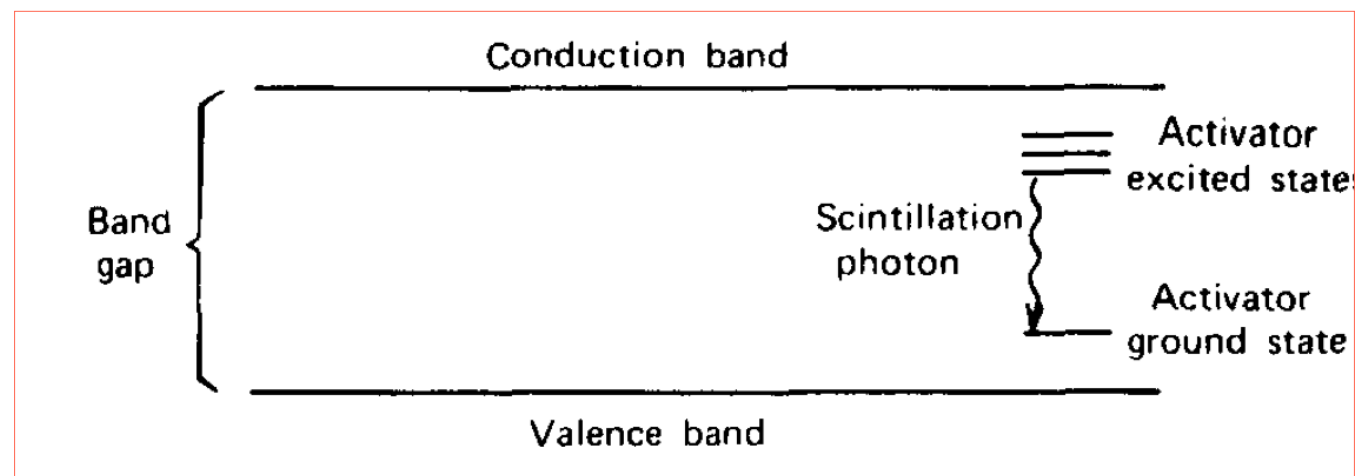
Data from Bengtson and Moszynski.⁴⁵

Table 7.2. Gaussian and exponential parameters for light pulse description from several plastic scintillators (from *Bengtson and Moszynski* [7.2])

Scintillator	σ [ns]	τ [ns]
NE102A	0.7	2.4
NE111	0.2	1.7
Naton 136	0.5	1.87

inorganic scintillators

The dominant decay time of the scintillation pulse is **230 ns for NaI(Tl)**, uncomfortably long for some fast timing or high counting rate applications. What determines this slow decay time? The pure crystal or the activator?



In addition to this prompt yield of NaI(Tl) (230 ns), a **phosphorescence** with characteristic **0.15 s decay time** has also been measured which contributes about 9% to the overall light yield.

Today

- Scintillation
 - Organic scintillators
 - Anthracene
 - Stilbene
 - Plastic
 - Liquid
 - Inorganic scintillators
 - NaI(Tl)
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 - Electrons
 - Gamma rays
 - Neutrons

Pulse shape discrimination

Slow light output component as a function of time produces a long tail which depends on the nature of the exciting particle/radiation.

The slow component fraction should depend primarily on the rate of energy loss dE/dx of the exciting particle and should be greatest for particles with large dE/dx . ($\alpha > \beta > \gamma$)

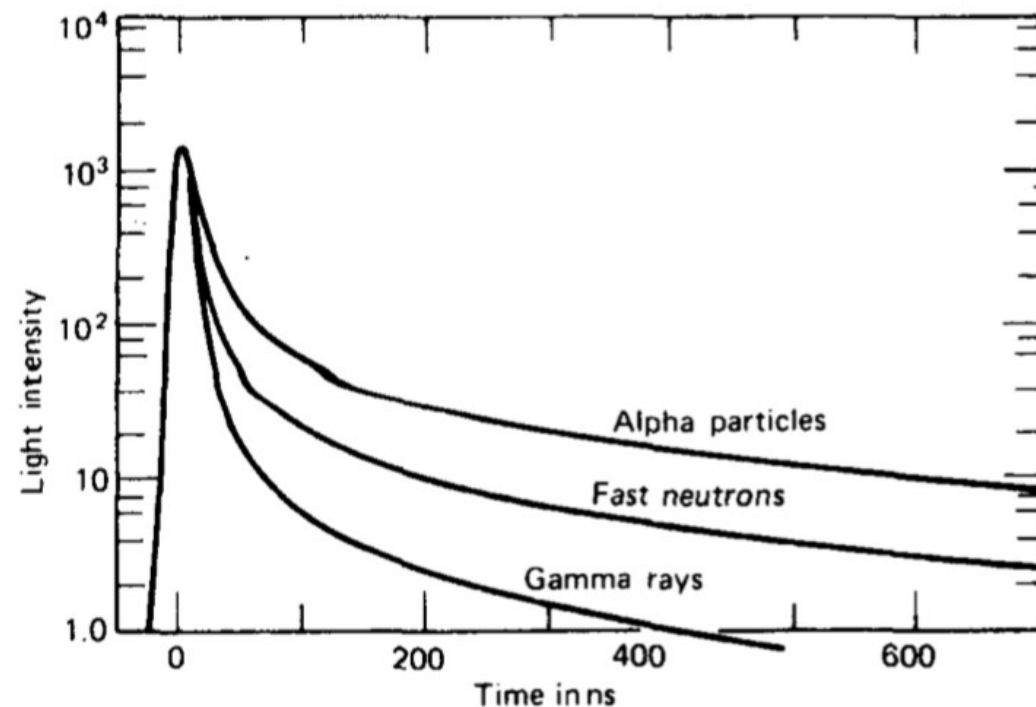
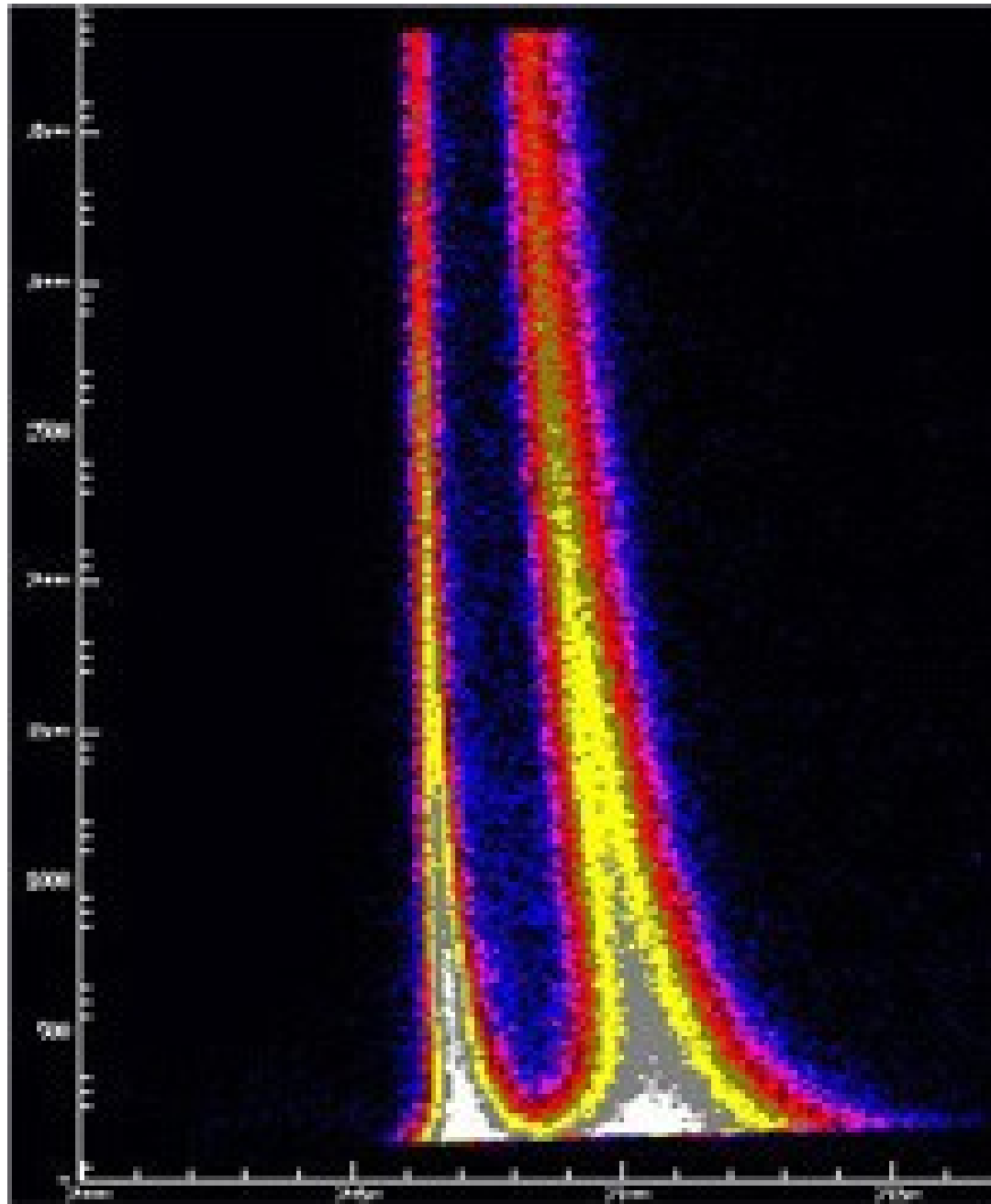


Figure 8.5 The time dependence of scintillation pulses in stilbene (equal intensity at time zero) when excited by radiations of different types. (From Bollinger and Thomas.⁶⁰)

PSD is used to **eliminate gamma-ray-induced events when organic scintillators are used as neutron detectors.**

stilbene and liquid scintillators

What about inorganic scintillators?



Otherway around:

LaBr₃(Ce) detectors have fast timing, i.e. good time resolution, compared to NaI(Tl).

We can then use them to **eliminate neutron induced events as LaBr₃(Ce) is used as gamma-ray detectors (OSCAR array at OCL).**

Example: Fission reaction produces a lot of neutrons in addition to gamma rays from the reaction products

Today

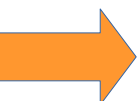
- Scintillation
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- Detector efficiency
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Table 7.3. Average energy loss per scintillator photon for electrons

Material	ϵ [eV/photon]
Anthracene	60
NaI	25
Plastic	100
BGO	300

- The light output of a scintillator refers more specifically to its efficiency for converting ionization energy to photons.
- The fraction of all incident particle energy which is converted into visible light is called “*scintillation efficiency*” or “*light output*”
- *Light output depends on the type of the radiation and energy*

Q: Can you tell the which type has the largest light output in Table 7.3?



Examples of light output for inorganic scintillators

- Deviations from linearity are less for inorganic scintillators.
- Non-linearity starts from 400 keV down to zero energy value
- We have to take care of this non-linearity (in the step of energy calibration of the detectors)

Perfectly linear response would correspond to a horizontal line

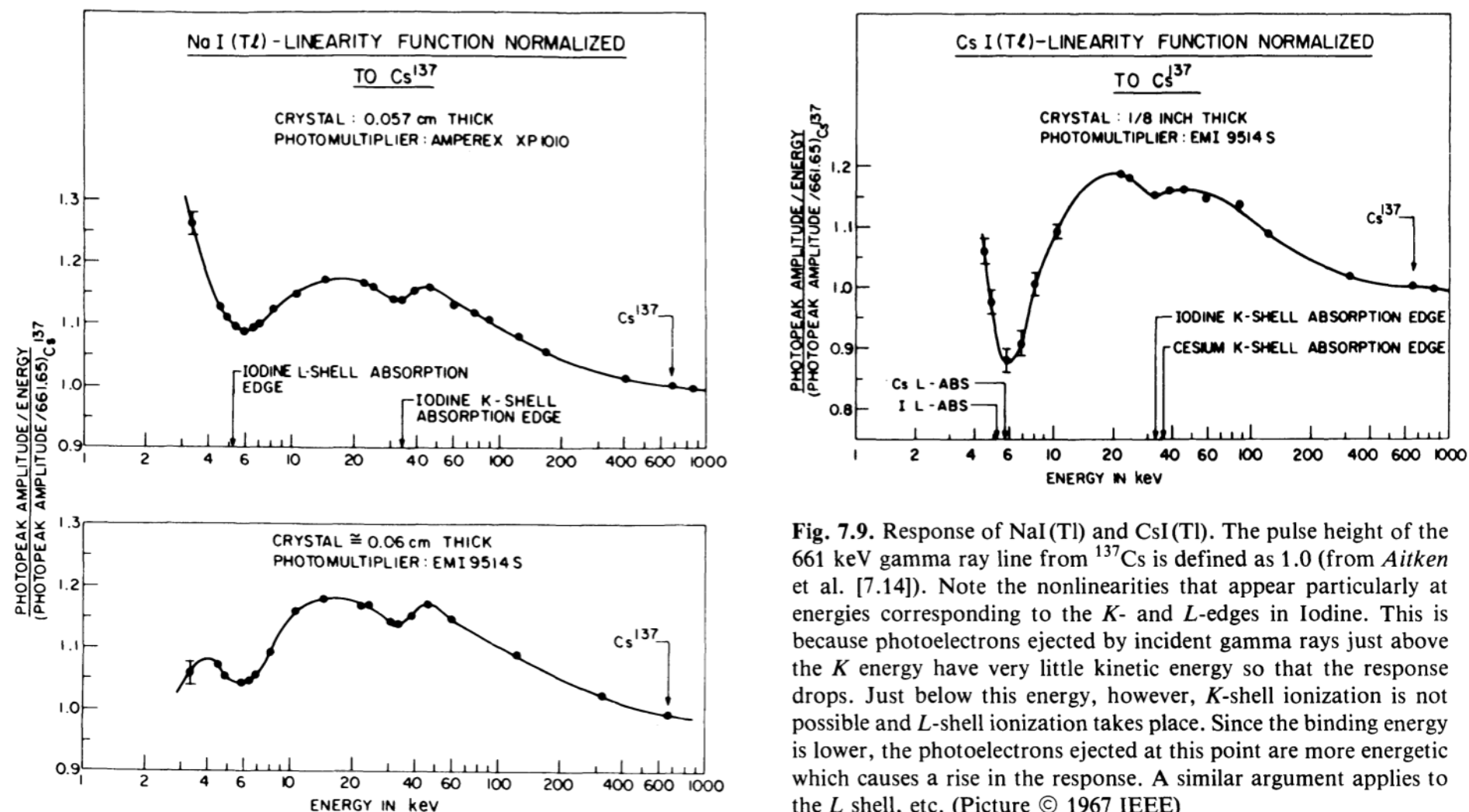


Fig. 7.9. Response of NaI(Tl) and CsI(Tl). The pulse height of the 661 keV gamma ray line from ^{137}Cs is defined as 1.0 (from Aitken et al. [7.14]). Note the nonlinearities that appear particularly at energies corresponding to the K - and L -edges in Iodine. This is because photoelectrons ejected by incident gamma rays just above the K energy have very little kinetic energy so that the response drops. Just below this energy, however, K -shell ionization is not possible and L -shell ionization takes place. Since the binding energy is lower, the photoelectrons ejected at this point are more energetic which causes a rise in the response. A similar argument applies to the L shell, etc. (Picture © 1967 IEEE)

Examples of light output for plastic (organic) scintillator

- Light output decreases for heavier particles
- Linearity is worsen for heavier particles.

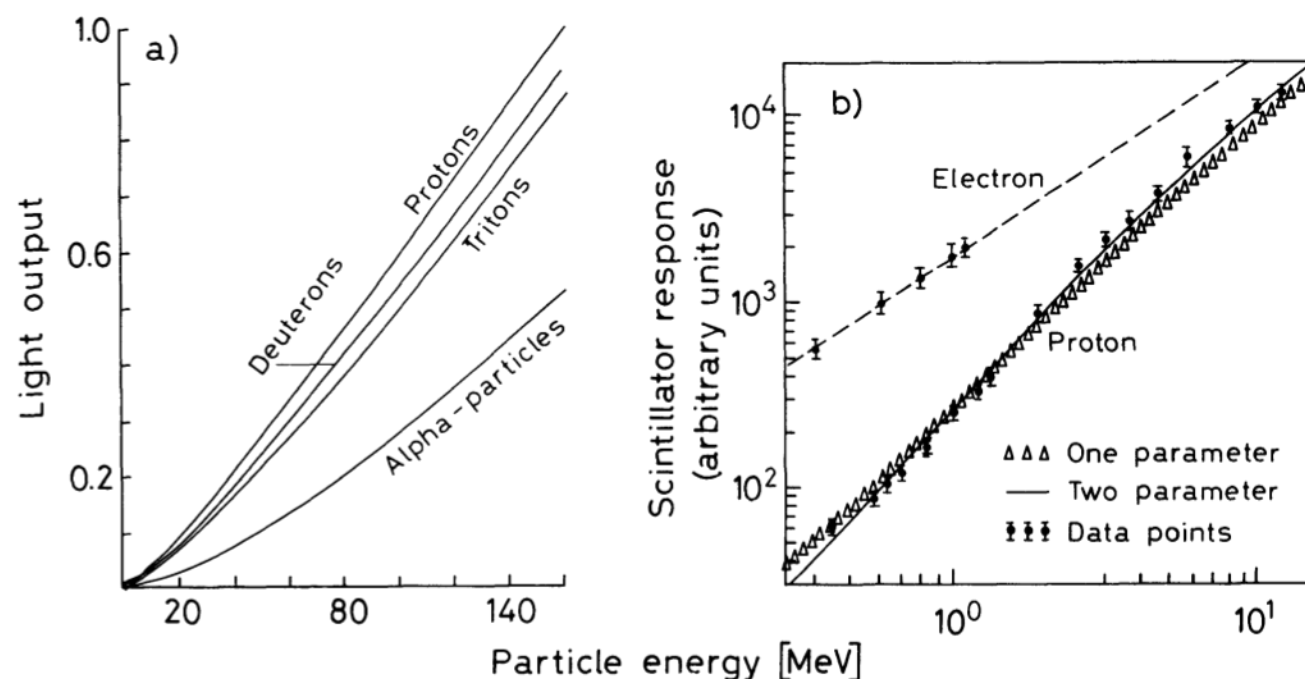


Fig. 7.8a, b. Response of NE102 plastic scintillator to different particles ((a) from Gooding and Pugh [7.6]; (b) from Craun and Smith [7.7])

Quenching interactions: Some energy loss is dissipated non-radiatively, primarily in the form of lattice “vibrations” or “heat”. These radiationless de-excitation processes are called “quenching”

Temperature dependence

The plot shows how sensitive is the decay time with temperature changes

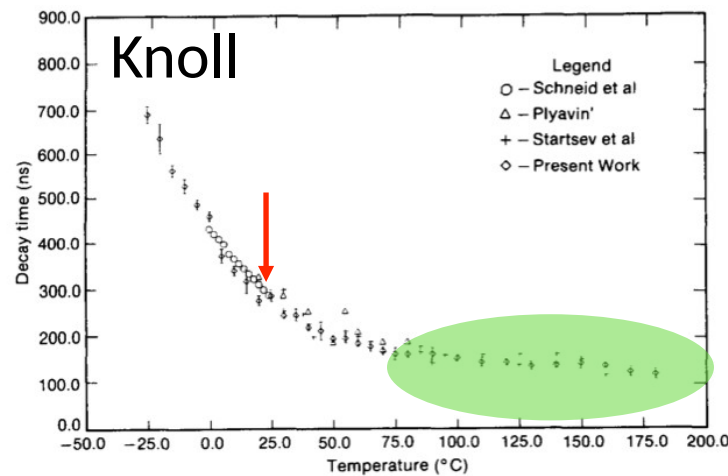
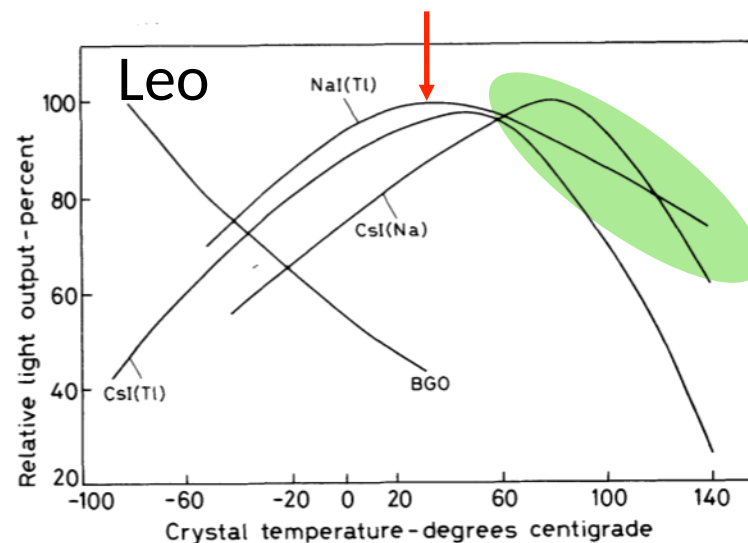


Figure 8.10 Temperature dependence of the scintillation decay time in NaI(Tl). (From Schweitzer and Ziehl.⁸³)



Inorganic scintillators work mostly in room temperatures.

- For some applications low decay time is desired.
- Can be obtained via high temperature
- However, light yield decreases significantly.

Organic scintillators have the same light output between the temperatures -60 to 20 °C i.e. less temperature dependent

Today

- Scintillation
 - Organic scintillators
 - Anthracene
 - Stilbene
 - Plastic
 - Liquid
 - Inorganic scintillators
 - NaI(Tl)
 - CsI(Tl)
 - LaBr₃(Ce)
 - BGO
- PMTs (Photomultiplier Tubes)
 - Mechanism
 - Photocathode
 - Quantum efficiency
- Time response
 - Organic
 - Inorganic
- Pulse shape discrimination
 - Organic
- Light output
 - Organic
 - Inorganic
- Energy resolution
 - Inorganic
- Detector efficiency
 - Heavy charged particle
 - Electrons
 - Gamma rays
 - Neutrons

Let's calculate energy resolution for a 662 keV gamma ray on a NaI(Tl) Detector

Table 7.3. Average energy loss per scintillator photon for electrons

Material	ϵ [eV/photon]
Anthracene	60
NaI	25
Plastic	100
BGO	300

$$E_\gamma = 662 \text{ keV}$$

$$N_{\text{photons}} = J = \frac{E_0}{\epsilon} = \frac{E_0}{W}$$

$$= \frac{662 \text{ keV}}{25 \text{ eV}}$$

$$= 26480 \text{ photons}$$

What about Fano factor?

Case 1:

For a detector in which the radiation energy is **not totally absorbed**, the number of signals producing reactions is given by a **Poisson distribution**. Fano factor=1

Scintillator

Case 2:

If the energy of the radiation is **fully absorbed** as is the case for detectors used in spectroscopy experiments, the Poisson statistics is incorrect. Fano factor $\ll 1$

**Gas
Solid-state
detectors**

Let's calculate energy resolution for a 662 keV gamma ray on a NaI(Tl) Detector

Table 7.3. Average energy loss per scintillator photon for electrons

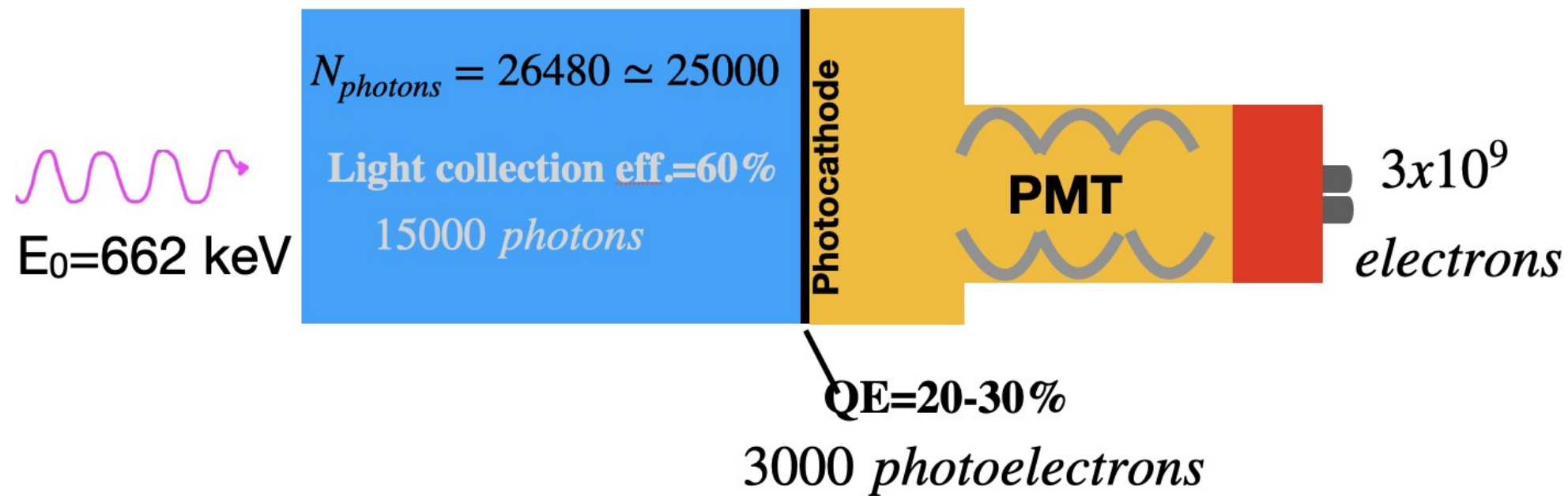
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BGO	300

$$E_\gamma = 662 \text{ keV}$$

$$N_{\text{photons}} = J = \frac{E_0}{\epsilon} = \frac{E_0}{w}$$

$$= \frac{662 \text{ keV}}{25 \text{ eV}}$$

$$= 26480 \text{ photons}$$



$$\frac{\Delta E_{FWHM}}{E_0} = 2.35 \frac{\sigma_J}{J} = 2.35 \frac{\sqrt{(3000)}}{3000} = 0.043 = 4.3\%$$

Light output or light yield has affect on the energy resolution.
While density of the scintillator has affect on its efficiency.

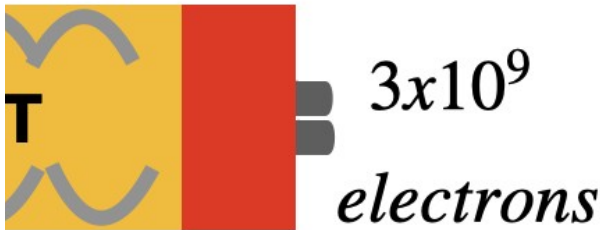
$$N_{photons} = 26480 \simeq 25000$$

Table 7.3. Average energy loss per scintillator photon for electrons

Material	ϵ [eV/photon]
Anthracene	60
NaI	25
Plastic	100
BGO	300

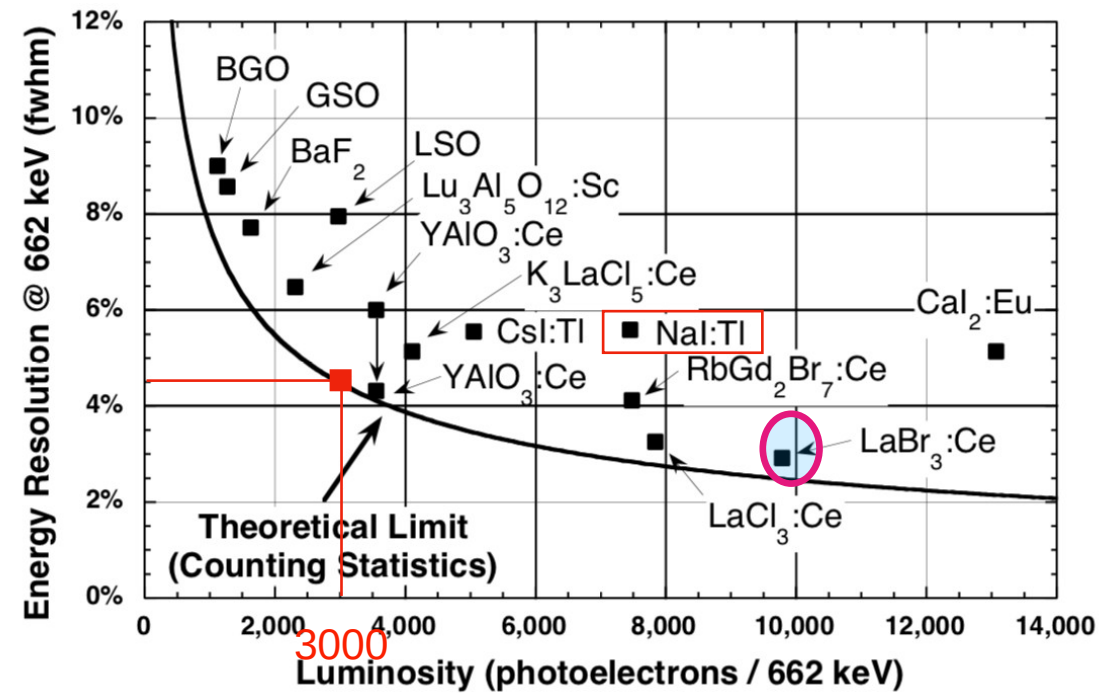
→ Best resolution

→ Highest efficiency



trons

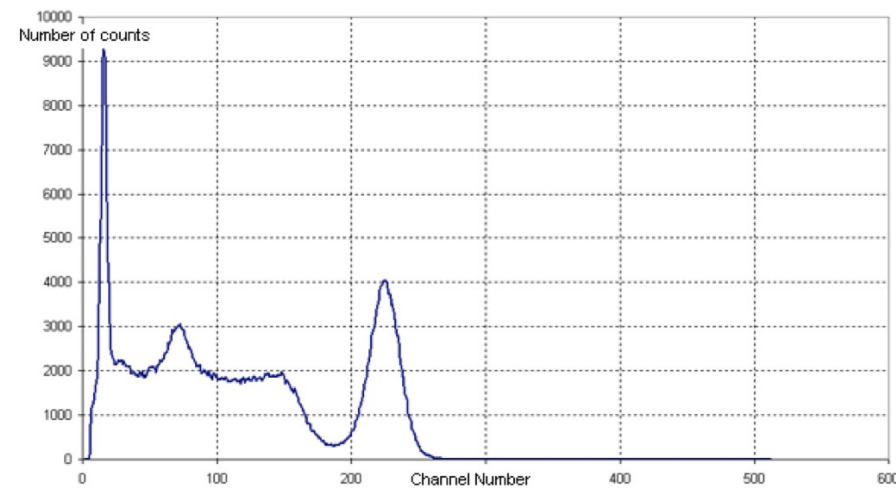
Light output or light yield has affect on the energy resolution.
While density of the scintillator has affect on its efficiency.



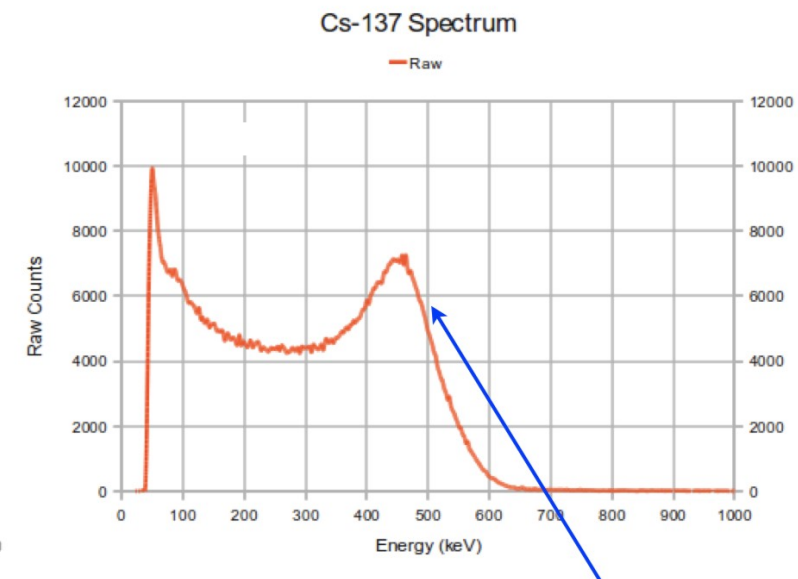
Resolution is never reached to the optimum value due to different losses in Scint. detectors.

Inorganic vs Organic

- ^{137}Cs spectrum in NaI crystal



same in plastic scintillator



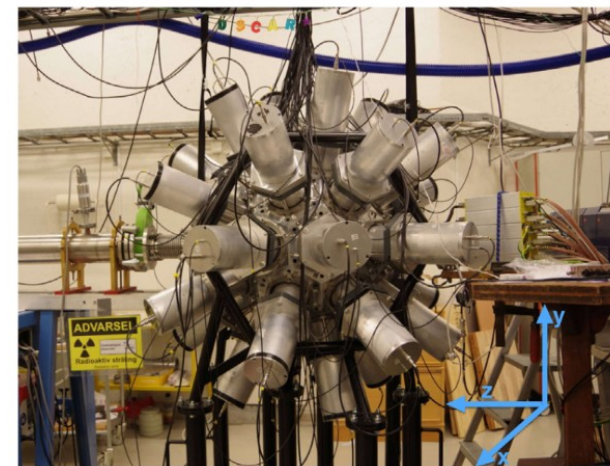
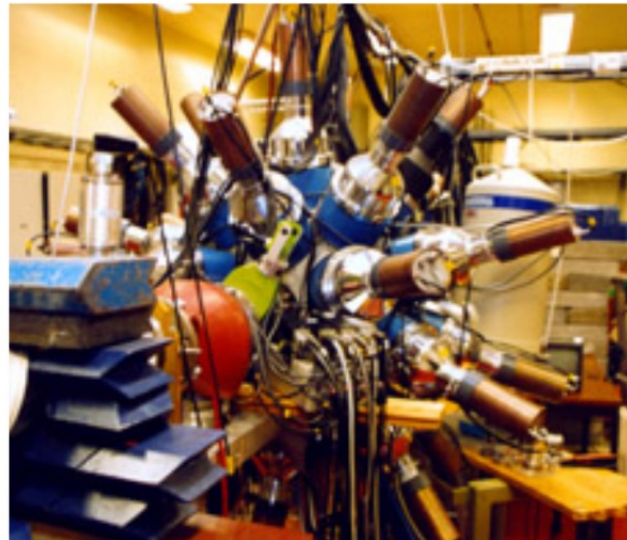
Compton edge or full peak?

Organic scintillators have low density (low-Z) (C and H only) while Photoelectric absorption is proportional to Z^4 or Z^5

CACTUS vs OSCAR

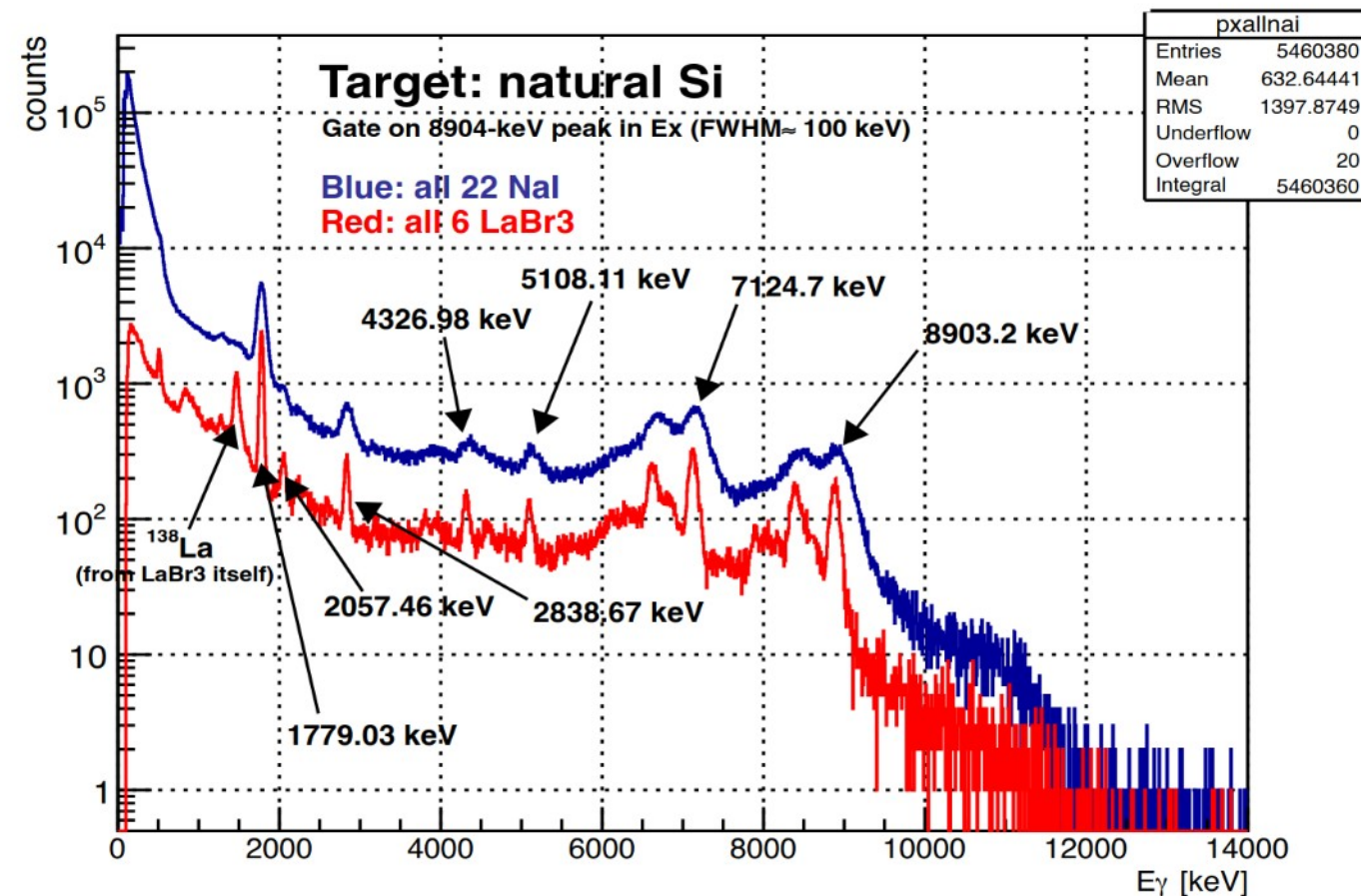
CACTUS Array

- 0 30 large volume NaI (TI) detectors.
- 0 Dimension: ($\varnothing$ 5 × 5 inches)



Oslo Scintillator Array (OSCAR)

- 0 30 large volume LaBr3(Ce) detectors.
- 0 Dimension: ($\varnothing$ 3.5 × 8 inches)



Comparison of energy resolutions

Not Today



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 - Stilbene
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 - CsI(Tl)
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 - Mechanism
 - Photocathode
 - Quantum efficiency
- Time response
 - Organic
 - Inorganic
- Pulse shape discrimination
 - Organic
- Light output
 - Organic
 - Inorganic
- Energy resolution
 - Inorganic
- Detector efficiency
 - Heavy charged particle
 - Electrons
 - Gamma rays
 - Neutrons

In-class activity: Friday, 24th October

Figure out detection efficiency for different types of radiation (for scintillation detectors).

Heavy-ions

Electrons

Gammas

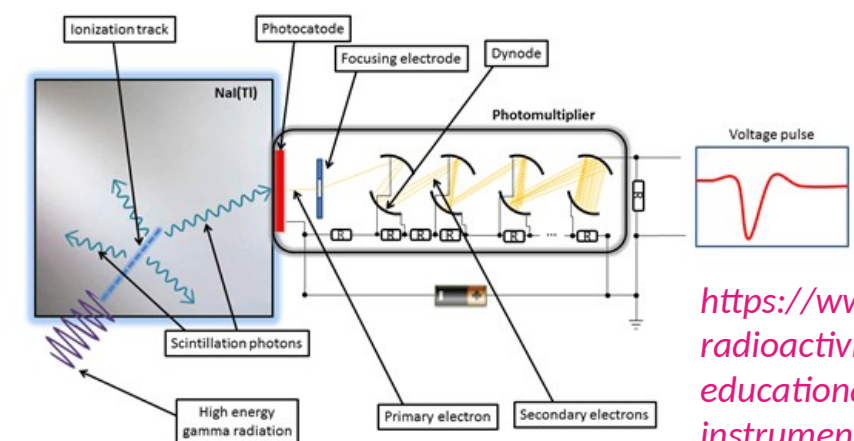
Neutrons

Questions to you

- 0 How do scintillator detectors work? What is the mechanism of a scintillator detector independent from its type? What properties are important to look at when comparing various types of scintillator materials?
- 0 Explain how scintillation light is produced in inorganic scintillator materials and why we dope inorganic scintillators.
- 0 Explain how an organic scintillator produces light. What is the desired process?
- 0 Compare organic and inorganic scintillators. List main differences.
- 0 How can you estimate the energy resolution of an inorganic scintillator detector? Feel free to give numerical explanations.

- 0 Which scintillator detector is optimum for:

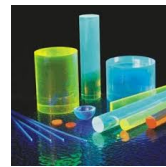
- beta particles
- alpha particles
- gamma rays
- Neutrons

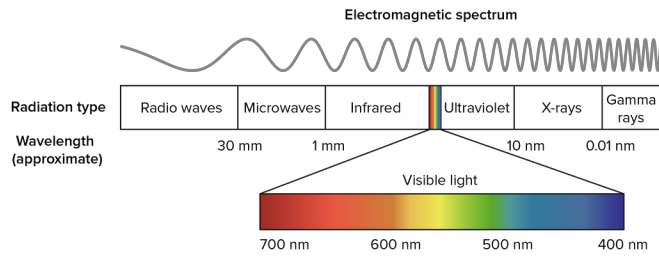


- 0 What are the advantages of LaBr₃ detectors compared to NaI(Tl) detectors?
- 0 Compare a typical gamma-ray pulse-height spectrum in organic and inorganic scintillator detector. Which one would you choose?
- 0 Explain how a PMT works and what it is used for. Draw and explain.

Lecture: Scintillation Detectors

**Chapters 7, 8.1, 8.2, 8.5, 8.6, 8.7
except 7.4 and 7.5,
(8.8, 8.9 and 9.7 are optional)**

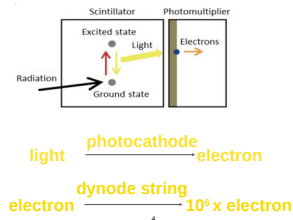




3

Wavelength is one of the characteristics we know about each scintillation material.

Scintillation mechanism:



when radiation strikes the scintillator it causes it to give off photons of visible light (that's the scintillation part). These photons pass through the crystal and they strike a thin metal foil called a photocathode – when this happens the light enters the second part of the detector, called a photo-multiplier tube (PMT). When the photon hits the photocathode it causes an electron to be ejected from the photocathode. Just past the photocathode there is a set of metal cups, each with a voltage applied to it (typically several hundred to a thousand volts) – the electron is accelerated by this voltage to a high energy and it strikes the cup with enough energy that it knocks loose a number of other electrons. Each of them, in turn, is accelerated towards the next metal cup, where each of the “new” electrons knocks loose a number of additional ones – by the end of the PMT the initial signal has been multiplied by a factor of a million or so. From there, it's up to the instrument manufacturer to figure out how they're going to use the light that's emitted.

Organic scintillators

Low-Z materials

Fast response time

High hydrogen content

Best for β particles and fast neutrons

Inorganic scintillators

High-Z materials

Dense

Slow response time

Best for γ rays

Note that heavy charged particles like protons, alpha particles, heavier mass nuclei.. We don't use scintillation detectors for their effective detection.

We use mainly gas detectors and Silicon semiconductor detectors.

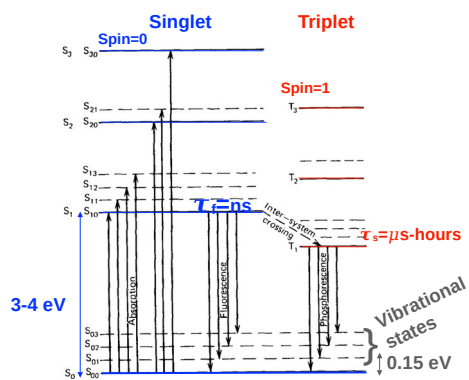
Today

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 - Organic scintillators
 - Anthracene
 - Stilbene
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 - Liquid
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- Detector efficiency
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 - Electrons
 - Gamma rays
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Today

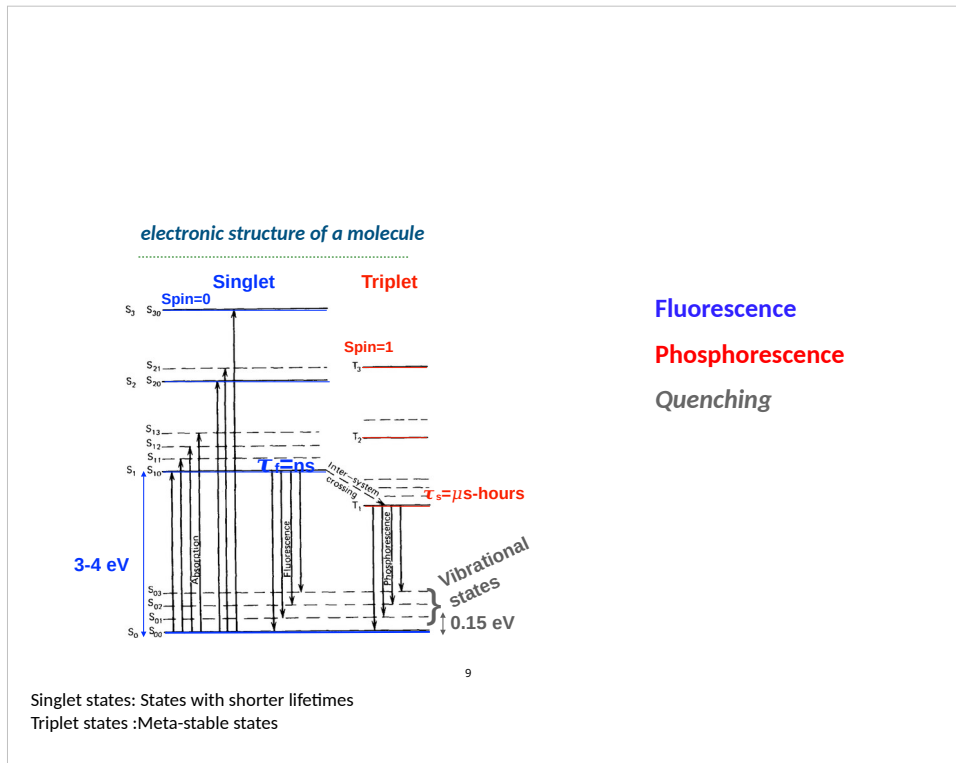
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electronic structure of a molecule



Thermal energy: 0.025 eV
In room temperature almost all molecules are in S_{00}

Singlet states: States with shorter lifetimes
Triplet states: Meta-stable states



Absorption is the energy (kinetic) given by the charged particle to the single molecule. Higher lying states, such as S_2, S_3 , decay to S_1 via radiationless internal conversion after 1 ps.

States with excess vibrational energy, such as S_{11}, S_{12}, S_{13} , lose their energies via vibrations.

The net effect of the excitation process in a simple organic crystal is to produce, after a negligibly short time period, a population of excited molecules in the S_{10} state.

Once the excited molecules are in the S_{10} state two processes might occur:

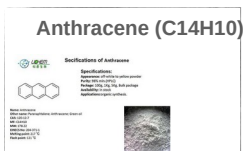
1- Fluorescence: emission of light by a substance that has absorbed light or another electromagnetic radiation of a different wave length. In most cases the emitted light has a longer wavelength. Emission occurs after **10ns!** **Prompt light emission**

2- Phosphorescence: Similar to Fluorescence, however the re-emission is not immediate. The transition between energy levels and the photon emission is delayed (**ms up to hours**). **Delayed light emission**

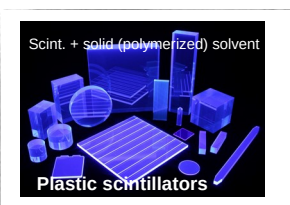
Important Note: Not all the kinetic energy by a charged particle is lost in a scintillator via fluorescent energy. Unfortunately. The remainder is dissipated non-radiatively, primarily in the form of lattice “vibrations” or “heat”. These radiationless de-excitation processes are called “quenching”. Impurities such as dissolved Oxygen in the organic scintillator creates quenching. Needs to be taken care.

organic crystal scintillators

Highest light output
Fragile



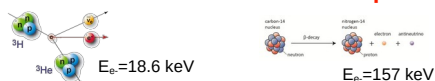
Low light output/fragile
Best separation between
charged particles and electrons



Can be used in large volumes
not fragile=flexible



Low radiation damage
Good for tritium and ¹⁴C in low-level β activity



10

Liquid scintillators are also widely applied to count radioactive material that can be dissolved as part of the scintillator solution. In this case, all radiations emitted by the source immediately pass through some portion of the scintillator and the counting efficiency can be almost 100%. The technique is widely used for counting low-level beta activity such as that from carbon-14 or tritium.

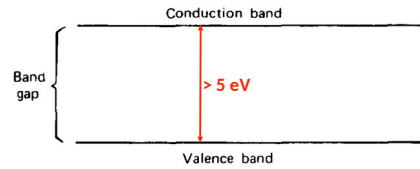
Liquid scintillator detectors in big dimensions are used for fast neutron detection.

Plastic scintillators have very fast timing response so that they are used for time of flight measurements for determining the flight time of the fast moving heavy charged particles. If we have two plastic scintillator with some distance, we can then extract the velocity of the moving particle!

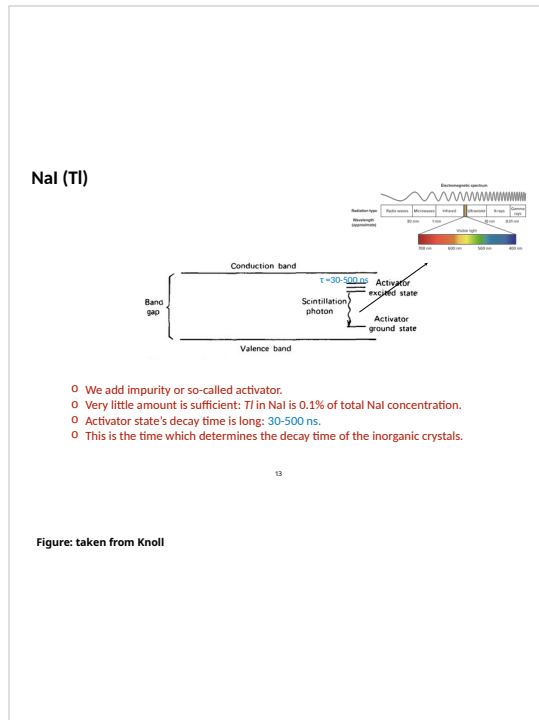
Today

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 - Organic
- Light output
 - Organic
 - Inorganic
- Energy resolution
 - Inorganic
- Detector efficiency
 - Heavy charged particle
 - Electrons
 - Gamma rays
 - Neutrons

pure NaI



- Inorganic scintillators are **insulators** where the forbidden band gap is larger than 5 eV
- Photons will not be emitted in the visible light range.



A charged particle passing through the detection medium will form a large number of electron-hole pairs created by the elevation of electrons from the valence to the conduction band. The positive hole will quickly drift to the location of an activator site and ionize it, because the ionization energy of the impurity will be less than that of a typical lattice site.

Meanwhile, the electron is free to migrate through the crystal and will do so until it encounters such an ionized activator. At this point the electron can drop into the activator site, creating a neutral configuration that can have its own set of excited energy states.

These states are illustrated in the figure above as horizontal lines within the forbidden gap. If the activator state that is formed is an excited configuration with an allowed transition to the ground state, its de-excitation will occur very quickly and with high probability for the emission of a corresponding photon. If the activator is properly chosen, this transition can be in the visible energy range.

Typical half-lives for such excited states are on the order of 50-500 ns. Because the migration time for the electron is much shorter, all the excited impurity configurations are formed essentially at once and will subsequently de-excite with the half-life characteristic of the excited state. It is the decay time of these states that therefore determines the time characteristics of the emitted scintillation light.

- Inorganic crystals are slower due to phosphorescence, i.e., slow timing response
- Longer decay time $\tau \sim 500 \text{ ns}$
- But high density and stopping power thus high efficiency --> gamma rays
- Highest light output, better energy resolution (compared to organic scintillators)
- A major disadvantage of certain inorganic crystals is **hygroscopicity**. NaI, in particular, is a prime example.

They get water molecules attached easily from the moisture in air. They are thus put into a protective airtight housing.

Photoelectric absorption cross section

$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

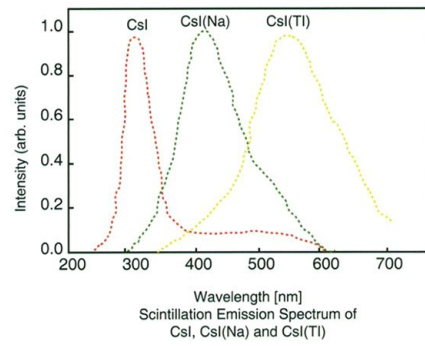
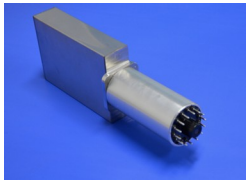
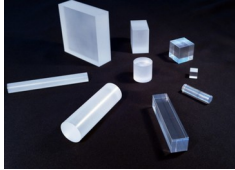
$$n=4 \text{ or } 5$$

NaI(Tl):
Na (Z=11)
I (Z=53) } $Z_{\text{eff}}: 50.8$

Nal (Tl)



CsI (Tl)



<https://www.shalomeo.com/Scintillators/CsI-Tl%20/product-393.html>

Lanthanum Bromide Scintillation Radiation Detectors

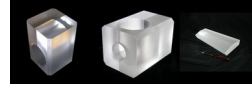
- High light output, and fast decay time output pulse.
- Better energy resolution and stability than NaI(Tl).
- Higher maximum throughput at high input count rates.

Lanthanum Bromide, or LaBr₃(Ce), is one of the new generation of inorganic scintillation gamma-ray detectors. LaBr detectors exhibit improved resolution and faster light decay time.



When used with the latest ORTEC digital electronics, these detectors provide improved resolution, pulse shape, and temperature stability compared to NaI(Tl) types.

BGO ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$)



High Z ($Z=83$), high density ($d=7.13$ g/cm³) scintillation material.

Only inorganic scintillator without activator

BGO is a very **efficient gamma ray absorber**.

$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

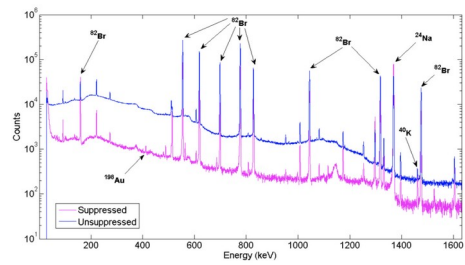
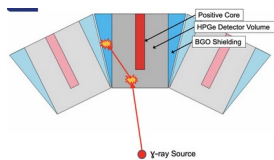
$n=4 \text{ or } 5$

High Z values cause large the **photo-fraction** for gamma ray absorption
very **good peak-to-total** ratios are observed.

Poor resolution. Why?? We will see it soon.

BGO ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$)

Compton Suppression Anti Compton Shields Calorimeter



[https://www.rsec.psu.edu/assets/PDF/8-RSEC_Book_Compton Suppression.pdf](https://www.rsec.psu.edu/assets/PDF/8-RSEC_Book_Compton%20Suppression.pdf)



Scintillation properties of inorganic materials

TABLE 6.1
Properties of Certain Inorganic Scintillators

Material	Wavelength of Maximum Emission (nm)	Scintillation Efficiency (Relative, %)	Decay Time (μ s)	Density (10^3 kg/m ³)
NaI(Tl)	410	100	0.23	3.67
CaF ₂ (Eu)	435	50	0.94	3.18
CsI(Na)	420	80	0.63	4.51
CsI(Tl)	565	45	1.00	4.51
Bi ₄ Ge ₃ O ₁₂	480	8	0.30	7.13
CdWO ₄	530	20	0.90	7.90
⁶ LiI(Eu)	470	30	0.94	3.49

Scintillation properties of organic materials

TABLE 6.3
Properties of Certain Organic Scintillators

Material	Wavelength of Maximum Emission (nm)	Relative Scintillation Efficiency (%)	Decay Time (ns)	Density (10^3 kg/m ³)
Anthracene	445	100	~30	1.25
trans-Stilbene	385	~60	4-8	1.16
NE 102	350-450	~65	2	1.06
NE 110	350-450	60	3	1.06
NE 213 (liquid)	350-450	~60	2	0.867
PILOT B	350-450	68	2	1.06
PILOT Y	350-450	64	~3	1.06

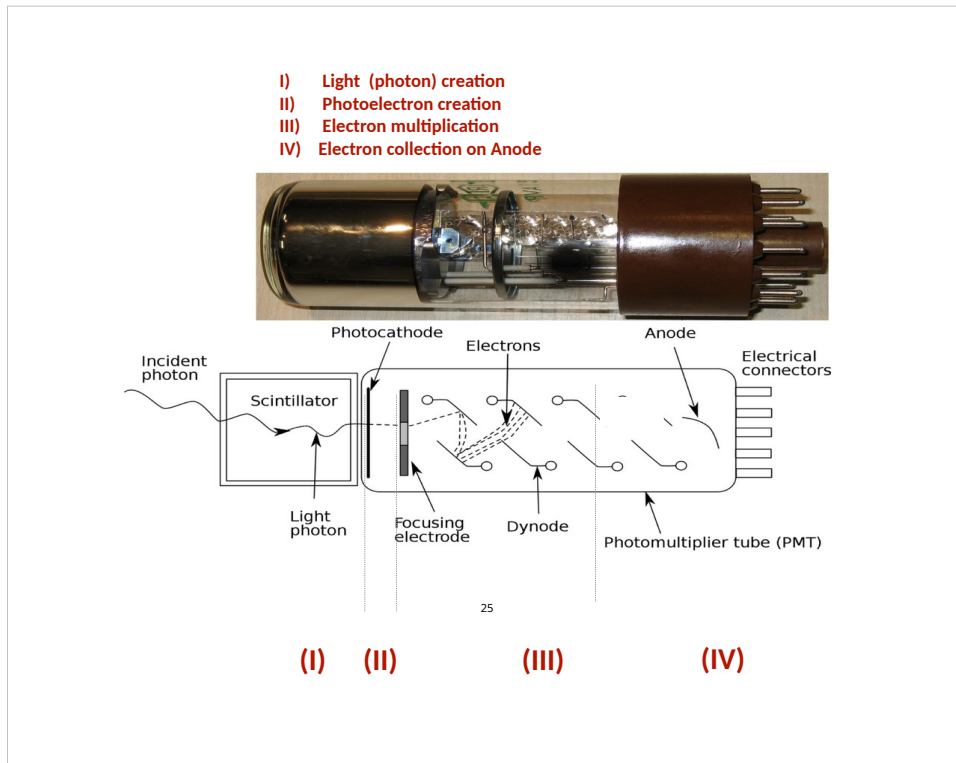
Taken from Measurement & Detection of Radiation N. Tsoulfanidis S. Landsberger

Today

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- Energy resolution
 - Inorganic
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 - Electrons
 - Gamma rays
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Photo multiplier tubes (PMTs)

- Scintillation material (organic and inorganic) will not work as a detector without a PMT tube
- Photocathode before PMT
- Anode after PMT



A potential "ladder" is set up along the length of the cathode - dynode - anode structure.

I) The incident photon excite the scintillator and creates light photons.

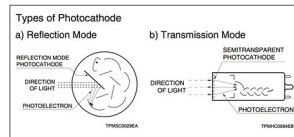
II) The light photon strikes the photocathode and an electron is emitted because of the Photoelectric Effect. This electron is called "photoelectron".

III) The applied voltage directs and accelerate the electron toward the first dynode, where upon striking, the electron transfers some of its energy to the electrons in the dynode. (Several hundred to a thousand Volts) . Secondary electrons are created! The process continues throughout the dynode ladder.

IV) At the anode, the cascade of electrons (10^6) is collected to give a current which can be amplified and analyzed.

Note: A Voltage divider is attached to the whole setup externally. It ensures that the photocathode, focusing grid, dynodes and the anode all have the appropriate potential for the PMT to multiply properly.

Photocathode



<https://www.hamamatsu.com/in/en/support/glossary/en.html>

not all photoelectrons will escape!! ~20-30% eff.

26

Type 1: A metal electrode where the light enters and the electrons exit from the same side. Used in double layers. (Reflective)

Type 2: A glass window in which the light strikes one surface and electrons exit from the opposite surface. More readily adaptable to PM tube designs. (Transitive)

photoemission: (1) the absorption of the incident photon and transfer of energy to an electron within the photoemissive material, (2) the migration of that electron to the surface, and (3) the escape of the electron from the surface of the photocathode.

Photocathode Quantum efficiency: 20-30% in NaI(Tl)

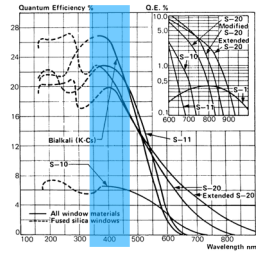


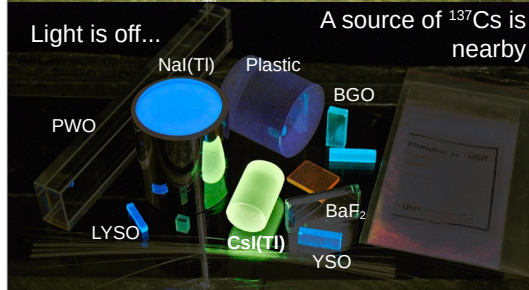
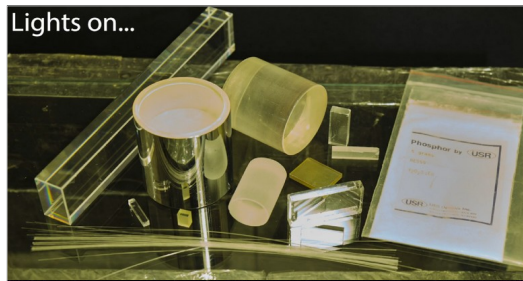
Table 8.1. Photocathode characteristics (from RTC catalog [8.3])

Cathode type	Composition	λ at peak response [nm]	Quantum efficiency at peak
Si (C)	Ag - O - Cs	400	0.36
S4	SbCs	800	16
Si1 (A)	SbCs	440	17
Super A	SbCs	440	22
Si2 (B)	SbCs	440	17
S20 (T)	SbNa - KCs	420	20
S20R	SbNa - KCs	550	8
TU	SbNa - KCs	420	20
Baikal1	SbK - Cs	420	26
Baikal1	Sb - K - Cs	400	26
Baikal1 DU	Sb - K - Cs	26	26
SB	Cs - Te	235	10

Most of the Photocathods used today are **semiconductor** materials where the QE is changing between 10 to 30%.

Photocathodes in **metal** form have very low QE around 0.1%! **Why?**

Answer: Photoelectron needs to escape from the PC. If it experiences a lot of free electrons, which is the case of metals, it will lose its energy due to the collisions with these free electrons. This will reduce the probability of the photoelectron to reach the surface with enough energy to overcome potential barrier and eventually escape.



NaI (Tl)

NP & HEP

CsI(Tl)

BaF₂ : Barium fluoride

Plastic

BGO: Bismuth Germanate (B₄Ge₃O₁₂)

YSO :Yttrium Silicon Oxide (Y₂SiO₅:Ce)

PET

LYSO: Lutetium Yttrium Silicon Oxide

Lu_{1.8}Y_{0.2}SiO₅:Ce)

PWO: Lead Tungstate (PbWO₄)

HEP (CERN)

Properties	BGO	LYSO
Density (g/m ³)	7.13	7.3
Melting Point (°C)	1050	2047
Index of Refraction	2.15	1.82
Radiation Length (cm)	1.10	1.16
Attenuation (cm ⁻¹)	0.96	0.87
Decay Constant (ns)	300	50
Light Yield (%) NaI (Tl)	25	75
Photofraction (%)	40	30
Energy Resolution (511 keV,%)	16	20
Radioactivity	No	Yes

Youtube video:

<https://www.youtube.com/watch?v=Gza6Cc8XOCA&t=537s>

Today

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 - LaBr₃(Ce)
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 - Photocathode
 - Quantum efficiency
- **Time response**
 - Organic
 - Inorganic
- Pulse shape discrimination
 - Organic
- Light output
 - Organic
 - Inorganic
- Energy resolution
 - Inorganic
- Detector efficiency
 - Heavy charged particle
 - Electrons
 - Gamma rays
 - Neutrons

organic scintillators

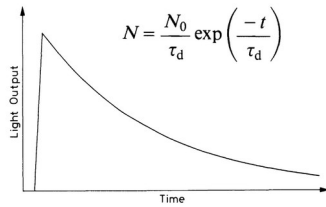


Fig. 7.2. Simple exponential decay of fluorescent radiation. The rise time is usually much faster than the decay time

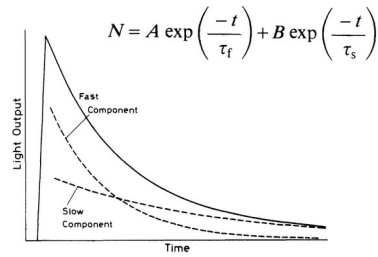


Fig. 7.3. Resolving scintillation light into *fast* (prompt) and *slow* (delayed) components. The *solid line* represents the total light decay curve

Decay from the optical levels

- Fast component
- Slow component

Early characterization papers assumed that light is observed via prompt events, i.e. fluorescence time to excite electrons in the molecules is too short compared to decay time.

But we have to consider also:
Delayed scintillation events, i.e. phosphorescence

organic scintillators

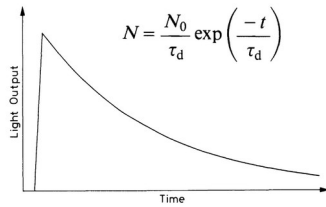


Fig. 7.2. Simple exponential decay of fluorescent radiation. The rise time is usually much faster than the decay time

Decay from the optical levels

- Fast component
- Slow component

Population of the optical levels, i.e. Excitation
Rise time

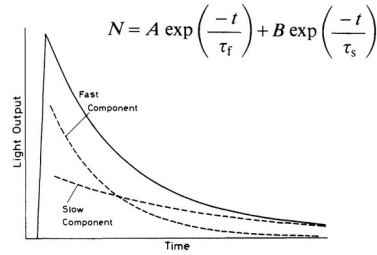


Fig. 7.3. Resolving scintillation light into *fast* (prompt) and *slow* (delayed) components. The *solid line* represents the total light decay curve

$$N(t) = N_0 f(\sigma, t) \exp\left(\frac{-t}{\tau}\right)$$

Table 7.2. Gaussian and exponential parameters for light pulse description from several plastic scintillators (from *Bengston and Moszynski* [7.2])

Scintillator	σ [ns]	τ [ns]
NE102A	0.7	2.4
NE111	0.2	1.7
Naton 136	0.5	1.87

Early characterization papers assumed that light is observed via prompt events, i.e. fluorescence time to excite electrons in the molecules is too short compared to decay time.

But we have to consider also:
Delayed scintillation events, i.e. phosphorescence

And also the finite time required to populate the luminescent states as they are comparable with the short decay time of the organic scintillators!

organic scintillators

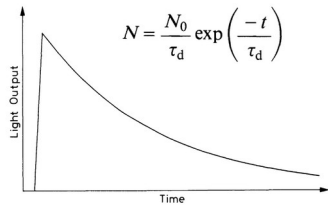


Fig. 7.2. Simple exponential decay of fluorescent radiation. The rise time is usually much faster than the decay time

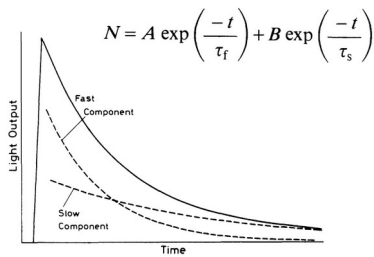


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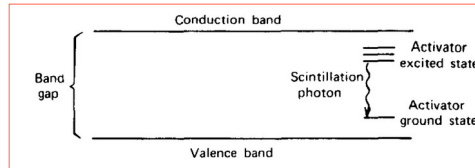
Table 8.2 Some Timing Properties of Fast Plastic Scintillators

	Parameters for Eq. (8.10)		Parameters for Eq. (8.11)		Measured FWHM
	τ_i (rise)	τ (decay)	σ_{ET}	τ	
NE 111	0.2 ns	1.7 ns	0.2 ns	1.7 ns	1.54 ns
Naton 136	0.4 ns	1.6 ns	0.5 ns	1.87 ns	2.3 ns
NE 102A	0.6 ns	2.4 ns	0.7 ns	2.4 ns	3.3 ns

Data from Bengtson and Moszynski.⁴⁵

inorganic scintillators

The dominant decay time of the scintillation pulse is **230 ns for NaI(Tl)**, uncomfortably long for some fast timing or high counting rate applications. What determines this slow decay time? The pure crystal or the activator?



In addition to this prompt yield of NaI(Tl) (230 ns), a **phosphorescence** with characteristic **0.15 s decay time** has also been measured which contributes about 9% to the overall light yield.

It is the activator which determines the decay time. Thallium (Tl) in the case of NaI(Tl). Since the light photons are created from the states of the activator and not the pure crystal.

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 - Mechanism
 - Photocathode
 - Quantum efficiency
- Time response
 - Organic
 - Inorganic
- **Pulse shape discrimination**
 - Organic
- Light output
 - Organic
 - Inorganic
- Energy resolution
 - Inorganic
- Detector efficiency
 - Heavy charged particle
 - Electrons
 - Gamma rays
 - Neutrons

Pulse shape discrimination

Slow light output component as a function of time produces a long tail which depends on the nature of the exciting particle/radiation.

The slow component fraction should depend primarily on the rate of energy loss dE/dx of the exciting particle and should be greatest for particles with large dE/dx . ($\alpha > \beta > \gamma$)

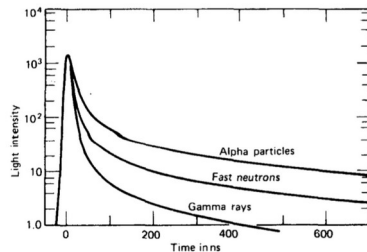


Figure 8.5 The time dependence of scintillation pulses in stilbene (equal intensity at time zero) when excited by radiations of different types. (From Bollinger and Thomas.⁶⁰)

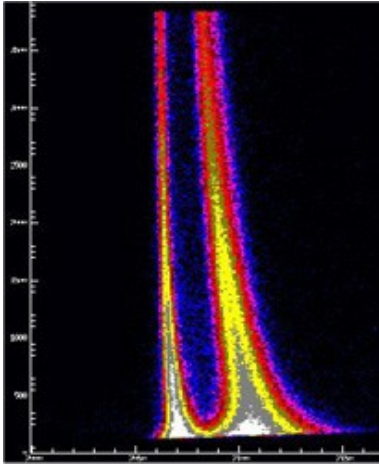
PSD is used to **eliminate gamma-ray-induced events when organic scintillators are used as neutron detectors.**

stilbene and liquid scintillators

One can therefore make use of this dependence to differentiate between particles of different kinds that deposit the same energy in the detector. This process is often called *pulse shape discrimination* and is widely applied to **eliminate gamma-ray-induced events when organic scintillators are used as neutron detectors.**

Mostly stilbene and liquid scintillators are used for pulse shape discrimination. These are the scintillation materials with large triplet concentration, i.e. high density of triplet states.

What about inorganic scintillators?



Otherway around:

LaBr₃(Ce) detectors have fast timing, i.e. good time resolution, compared to NaI(Tl).

We can then use them to **eliminate neutron induced events as LaBr₃(Ce) is used as gamma-ray detectors (OSCAR array at OCL).**

Example: Fission reaction produces a lot of neutrons in addition to gamma rays from the reaction products

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Table 7.3. Average energy loss per scintillator photon for electrons

Material	ϵ [eV/photon]
Anthracene	60
NaI	25
Plastic	100
BGO	300

- The light output of a scintillator refers more specifically to its efficiency for converting ionization energy to photons.
- The fraction of all incident particle energy which is converted into visible light is called "*scintillation efficiency*" or "*light output*".
- *Light output depends on the type of the radiation and energy*

Q: Can you tell the which type has the largest light output in Table 7.3?

38

Light output response
for inorganic and organic
scintillators. Next slides.



Answer: The NaI(Tl) has the largest light output which gives the best energy resolution compared to Anthracene, Plastic and BGO in the table

However, we have to remember that photocathode/photomultiplier has its efficiency about 20-30% which we have to take into account for the resolution of this detector and for any given scintillator!

Examples of light output for inorganic scintillators

- Deviations from linearity are less for inorganic scintillators.
- Non-linearity starts from 400 keV down to zero energy value
- We have to take care of this non-linearity (in the step of energy calibration of the detectors)

Perfectly linear response would correspond to a horizontal line

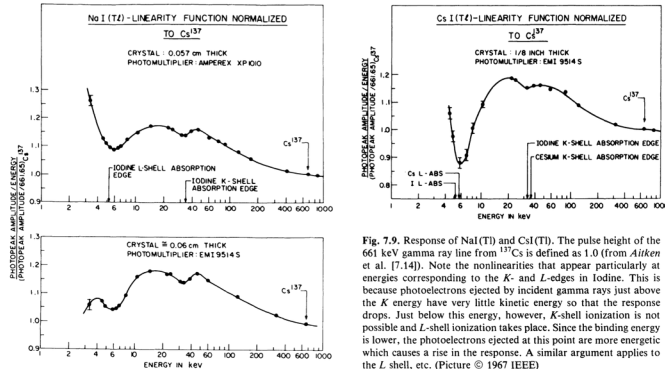


Fig. 7.9. Response of NaI(Tl) and CsI(Tl). The pulse height of the 661 keV gamma ray line from ^{137}Cs is defined as 1.0 (from Aitken et al. [7.14]). Note the nonlinearities that appear particularly at energies corresponding to the K - and L -edges in iodine. This is because photoelectrons ejected by incident gamma rays just above the K energy have very little kinetic energy so that the response drops. Just below this energy, however, K -shell ionization is not possible and L -shell ionization takes place. Since the binding energy is lower, the photoelectrons ejected at this point are more energetic which causes a rise in the response. A similar argument applies to the L shell, etc. (Picture © 1967 IEEE)

Read page# 170 in Leo, including Figure 7.9.

Examples of light output for plastic (organic) scintillator

- Light output decreases for heavier particles
- Linearity is worsen for heavier particles.

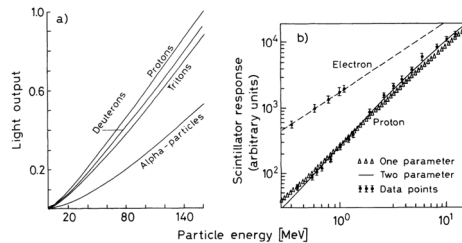


Fig. 7.8a, b. Response of NE102 plastic scintillator to different particles ((a) from Gooding and Pugh [7.6]; (b) from Craun and Smith [7.7])

Quenching interactions: Some energy loss is dissipated non-radiatively, primarily in the form of lattice “vibrations” or “heat”. These radiationless de-excitation processes are called “quenching”

Linearity has dependency not only on the incoming energy but also the type of the particle.

Alphas have worst response: more ionizing particles = high ionization power. (dE/dx must be playing an important role)

The first successful semi-empirical model for non-linearity behaviour was proposed by Birks et al. in 1951.

He explained that the deviations as being due to quenching interactions between the excited molecules created along the path of incident particle, i.e., interactions which drain energy which would otherwise go into luminescence. Since a higher ionizing power produces a higher density of excited molecules, more quenching interactions will take place for these particles.

Temperature dependence

The plot shows how sensitive is the decay time with temperature changes

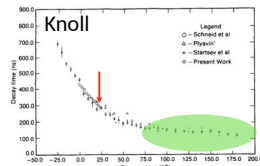
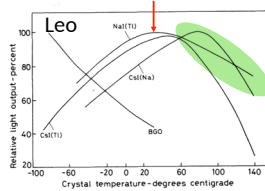


Figure 8.10 Temperature dependence of the scintillation decay time in NaI(Tl). (From Schweitzer and Ziehl¹⁰)



Inorganic scintillators work mostly in room temperatures.

- For some applications low decay time is desired.
- Can be obtained via high temperature
- However, light yield decreases significantly.

Organic scintillators have the same light output between the temperatures -60 to 20 °C i.e. less temperature dependent

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Let's calculate energy resolution for a 662 keV gamma ray on a NaI(Tl) Detector

Table 7.3. Average energy loss per scintillator photon for electrons

Material	ϵ [eV/photon]
Anthracene	60
NaI	25
Plastic	100
BGO	300

$E_\gamma = 662 \text{ keV}$

$$N_{photons} = J = \frac{E_0}{\epsilon} = \frac{E_0}{w}$$

$$= \frac{662 \text{ keV}}{25 \text{ eV}}$$

$$= 26480 \text{ photons}$$

43

What about Fano factor?

Case 1:

For a detector in which the radiation energy is **not totally absorbed**, the number of signals producing reactions is given by a **Poisson distribution**. **Fano factor=1**

Scintillator

Case 2:

If the energy of the radiation is **fully absorbed** as is the case for detectors used in spectroscopy experiments, the Poisson statistics is incorrect. Fano factor $\ll 1$

**Gas
Solid-state
detectors**

Let's calculate energy resolution for a 662 keV gamma ray on a NaI(Tl) Detector

Table 7.3. Average energy loss per scintillator photon for electrons

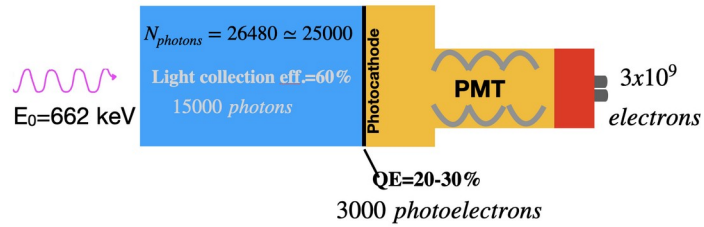
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$E_\gamma = 662 \text{ keV}$

$$N_{photons} = J = \frac{E_0}{\epsilon} = \frac{E_0}{W}$$

$$= \frac{662 \text{ keV}}{25 \text{ eV}}$$

$$= 26480 \text{ photons}$$



$$\frac{\Delta E_{FWHM}}{E_0} = 2.35 \frac{\sigma_J}{J} = 2.35 \frac{\sqrt{(3000)}}{3000} = 0.043 = 4.3\%$$

Light output or light yield has affect on the energy resolution.
While density of the scintillator has affect on its efficiency.

$$N_{\text{photons}} = 26480 \approx 25000$$

Table 7.3. Average energy loss per scintillator photon for electrons

Material	ϵ [eV/photon]
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NaI	25
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BGO	300

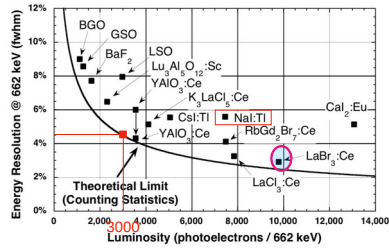
→ Best resolution

→ Highest efficiency

3×10^9
electrons

trons

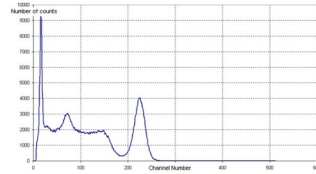
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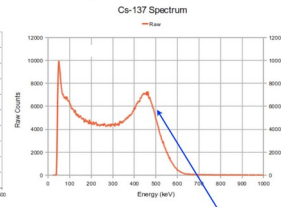
Resolution is never reached to the optimum value due to different losses in Scint. detectors.

Inorganic vs Organic

- ^{137}Cs spectrum in NaI crystal



same in plastic scintillator



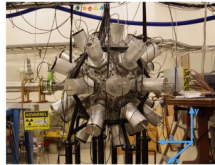
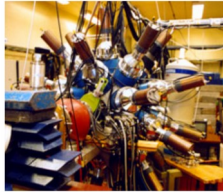
Compton edge or full peak?

Organic scintillators have low density (low-Z) (C and H only) while Photoelectric absorption is proportional to Z^4 or Z^5

CACTUS vs OSCAR

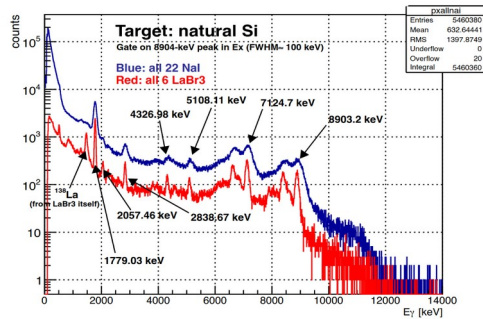
CACTUS Array

- 0 30 large volume NaI (TI) detectors.
- 0 Dimension: ($\varnothing$ 5 × 5 inches)



Oslo Scintillator Array (OSCAR)

- 0 30 large volume LaBr3(Ce) detectors.
- 0 Dimension: ($\varnothing$ 3.5 × 8 inches)



Comparison of energy resolutions

Not Today 😊

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 - Electrons
 - Gamma rays
 - Neutrons

In-class activity: Friday, 24th October

Figure out detection efficiency for different types of radiation (for scintillation detectors).

Heavy-ions

Electrons

Gammas

Neutrons

Questions to you

- How do scintillator detectors work? What is the mechanism of a scintillator detector independent from its type? What properties are important to look at when comparing various types of scintillator materials?
- Explain how scintillation light is produced in inorganic scintillator materials and why we dope inorganic scintillators.
- Explain how an organic scintillator produces light. What is the desired process?
- Compare organic and inorganic scintillators. List main differences.
- How can you estimate the energy resolution of an inorganic scintillator detector? Feel free to give numerical explanations.
- Which scintillator detector is optimum for:
 - beta particles
 - alpha particles
 - gamma rays
 - Neutrons
- What are the advantages of LaBr₃ detectors compared to NaI(Tl) detectors?
- Compare a typical gamma-ray pulse-height spectrum in organic and inorganic scintillator detector. Which one would you choose?
- Explain how a PMT works and what it is used for. Draw and explain.

