Chapter IX:
Detectors based on scintillation

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- Introduction
- Organic scintillators
- Inorganic crystals
- Photomultipliers
- Spectrometry γ with NaI(Tl)

Introduction

- When ionizing radiation interacts with matter → a large number of molecules are excited or ionized
- When these molecules return to the ground state → possible creation of luminescence centers (light emission point during e^--h^+ recombination) → possible emission of photons in the visible or near to the visible energy range → radioluminescence, luminescence or scintillation
- The number of emitted photons $N_{h\nu} \propto E_{abs}$ in the medium
- One of the most widely used particle detection devices are based on this principle: scintillation detectors or photoscintillators
- Emitted light is converted into an electrical pulse by photomultiplier tube or photodiode

Luminescence

3 types of Luminescence:

1. Fluorescence: very short lifetime of the luminescence center → light emission occurs “immediately” after absorption (more precisely: < 10^{-8} s, i.e. time for atomic transition)
2. Phosphorescence: light emission is delayed because excited state is metastable (time between absorption and emission can be from μs to days, months)
3. Delayed fluorescence: a center of phosphorescence can be transformed into a fluorescence center following an external excitation → “normal” fluorescence but after a much longer time

Properties of a “good” scintillator

- The conversion of kinetic energy of the ionizing radiation into detectable light should have high efficiency
- The amount of light emitted should be proportional to the energy deposited by the ionizing particle
- Material should be transparent to the wavelength of its own scintillation light
- The decay time of the induced luminescence should be little or zero
- The light pulses should be as short as possible
- The refractive index of the material should preferably be close to 1.5 (*n* of glass) to permit efficient coupling of the scintillation light to a photomultiplier tube or other light sensor in glass
- The material should be chemically and mechanically stable, not too difficult to produce and not too expensive

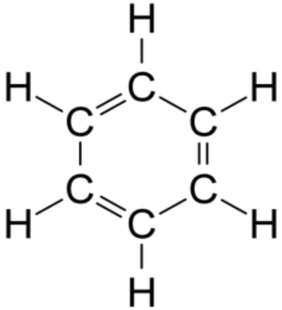
Types of scintillators

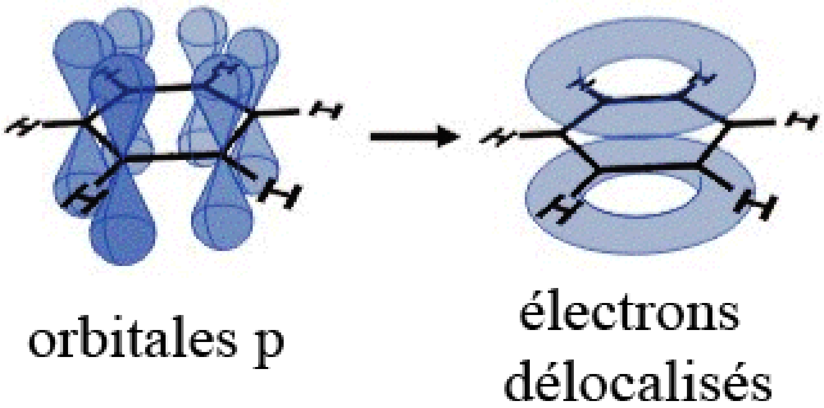
- No material shows all these properties → for a particular application: compromise between luminescence properties and those required by application
- Moreover, dimensions of scintillator depends on the type of radiation (larger dimensions for γ rays)
- Two important “families” of scintillators:
  1. Organic scintillators (crystal, liquid, plastic, gas) principally composed of H, C and O → molecular fluorescence
  2. Inorganic scintillators (crystal, glass, gas) → crystalline fluorescence
- A third type exists but rarely used → rare gases → atomic fluorescence

Organic scintillator: example of benzene (1)

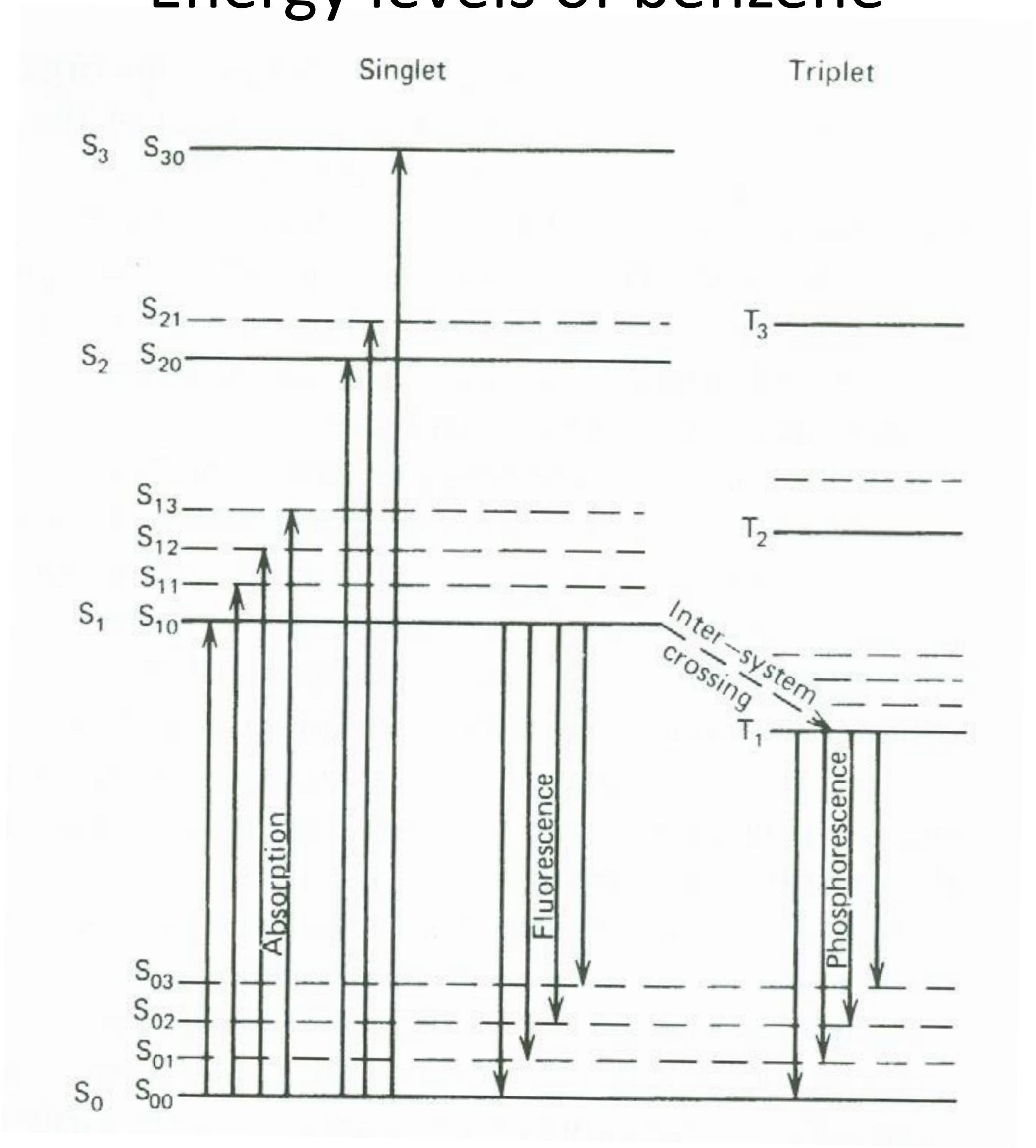
- Most of organic scintillators are constituted of molecules with delocalized electrons → example of benzene (C_6H_6) which has an hexagonal form
- The σ e^- are on localized orbitals and bind C and H atoms
- The 6 π e^- are delocalized on orbitals which are on both sides of the molecule plane → They can have a spin = 0 (singlet: S) or a spin = 1 (triplet: T) → we note their electronic state by a first index and their vibration state by a second index
- The energy difference between the electronic states S_0 and S_1 is ≈ 3-4 eV
- The energy difference between the vibration states is ≈ 0.15 eV
- At room temperature → rotation states are ignored because their energy difference is weak
- At room temperature → all the e^- are in the fundamental state S_{00} (the energy differences are quite larger than 0.025 eV)

Organic scintillator: example of benzene (2)





Energy levels of benzene



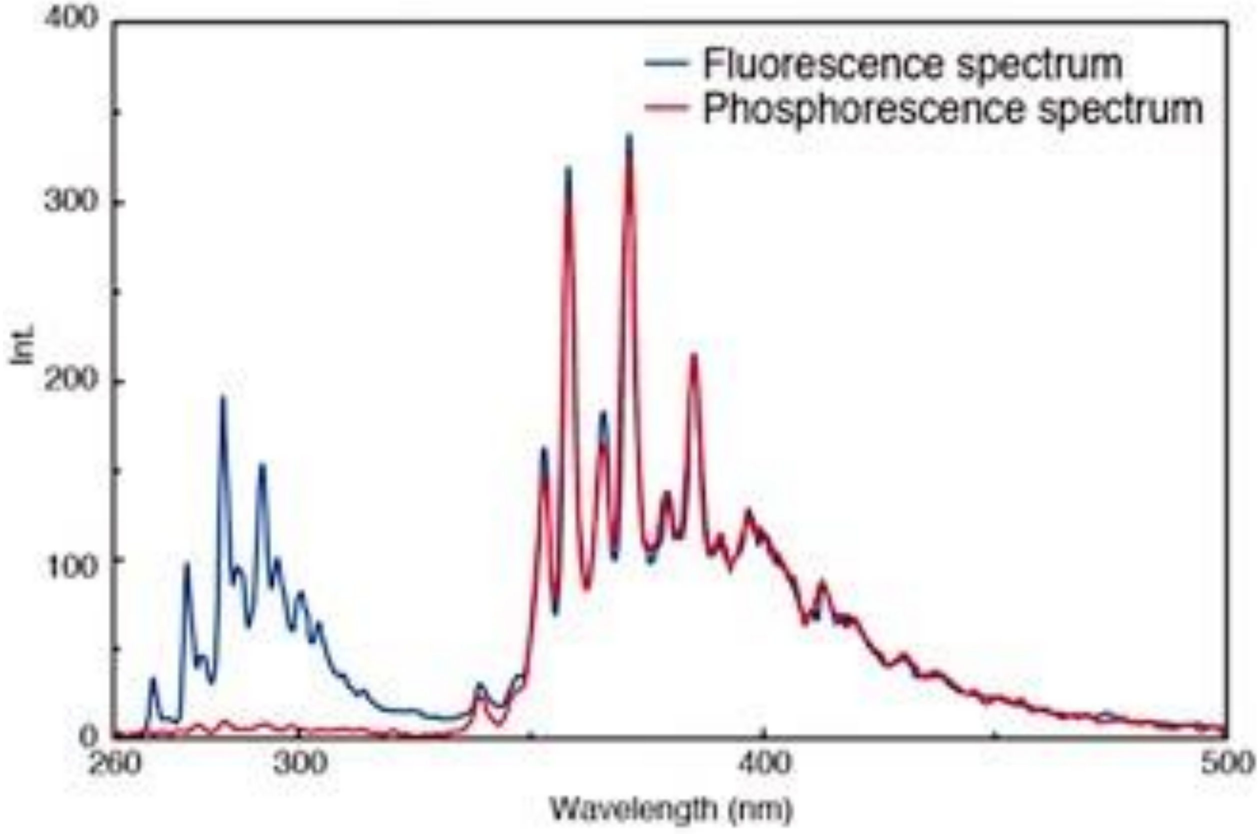
Scintillation mechanisms : Fluorescence

1. An ionizing particle crosses the scintillator and produces ionizations and excitations → the excitations of e^- in singlet states are at the origin of the fluorescence while ionizations does not give rise to a light emission → can be responsible of nonlinear effects
2. After the absorption of energy → molecule in an excited electronic state
3. Very quickly (≈ ps) high level electronic states decay without photon emission (« radiationless internal conversion ») → molecule in the state S_1
4. The transitions between the vibrational states of one band are radiationless → dissipation of the energy as heat → the molecule reaches its thermal equilibrium → S_{10} state (after time ≈ ps)
5. Then decay (dipolar electric transition) to S_{0i} state with photon emission (with t ≈ ns) → fluorescence
6. Finally radiationless transition → S_{00}

Scintillation mechanisms: Phosphorescence

- For triplet states → same process → molecules are finally in the T_1 triplet state (either directly during the energy absorption either indirectly from the S_1 state (« inter-system crossing »)
- The transitions from T_1 to S_0 are strongly forbidden due to selection rules of multipolar transitions (spin difference) but possible
- The lifetime of the T_1 state is thus long (≈ 1 ms in this case → it can be still longer) → delayed photons emission → phosphorescence
- The T energy levels < than S levels → phosphorescence wavelength > fluorescence wavelength

Fluorescence and phosphorescence spectra



Luminescence spectrum of benzene (excitation at 255 nm for 77 K) → blue: normal emission ↔ red: phosphorescence spectrum measured with a delay of 5 ms

Scintillation mechanisms: Delayed fluorescence

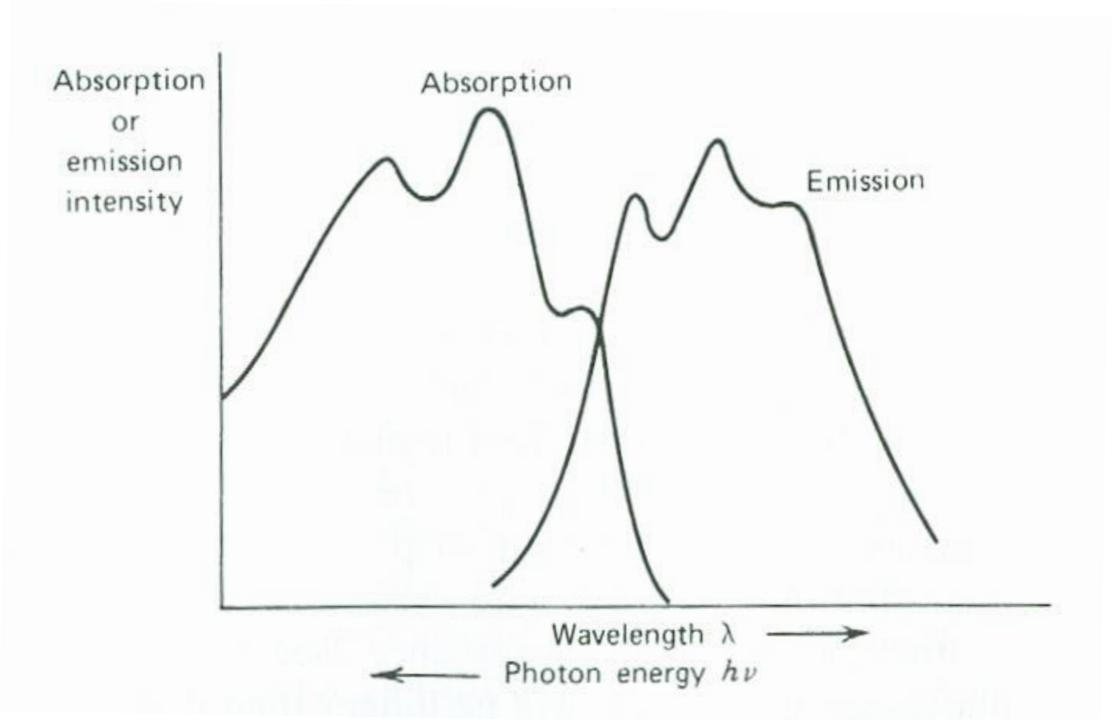
- In the T_{10} metastable state → molecules can be excited to S_{10} state due to a controlled external stimulus → delayed fluorescence
- Thermal stimulation → application: thermoluminescent dosimeters (TLD)
- Optical stimulation (UV, visible, IR) → application: optically stimulated luminescence dosimeters (OSL)

Properties of organic scintillators

- Absorption end emission spectra
- Light response
- Time response
- Types of scintillators
- Applications of organic scintillators

Absorption and emission spectra for organic scintillators

- Energy between S_{10} and S_{0i} < energy between S_{00} and S_{1i} → no (or little) superposing of absorption and emission spectra (Stokes shift)
- A scintillator is thus quasi transparent to its own luminescence light ↔ only little self-absorption of the fluorescence



Light response of an organic scintillator (1)

- Only a small fraction of the kinetic energy lost by the incident radiation in the scintillator is converted into fluorescence energy (i.e. into photons) → the remaining is radiationless dissipated → principally into heat (vibrations of the lattice)
- This energy emitted by fluorescence is called the light response of the scintillator, *L* →

$$L = E_{h\nu} = \langle N_{h\nu} \rangle \langle h\nu \rangle$$

with $\langle N_{h\nu} \rangle$ the mean number of photons emitted and $\langle h\nu \rangle$ their mean energy

- We define the intrinsic efficiency of the scintillator as the fraction of energy lost by the ionizing particle (E_{abs}) which is converted into light energy →

$$S = \frac{L}{E_{abs}}$$

Light response of an organic scintillator (2)

- Generally → S is small (≈ 1-2%)
- We have thus the mean energy lost *W* by the particle for each emitted photon →

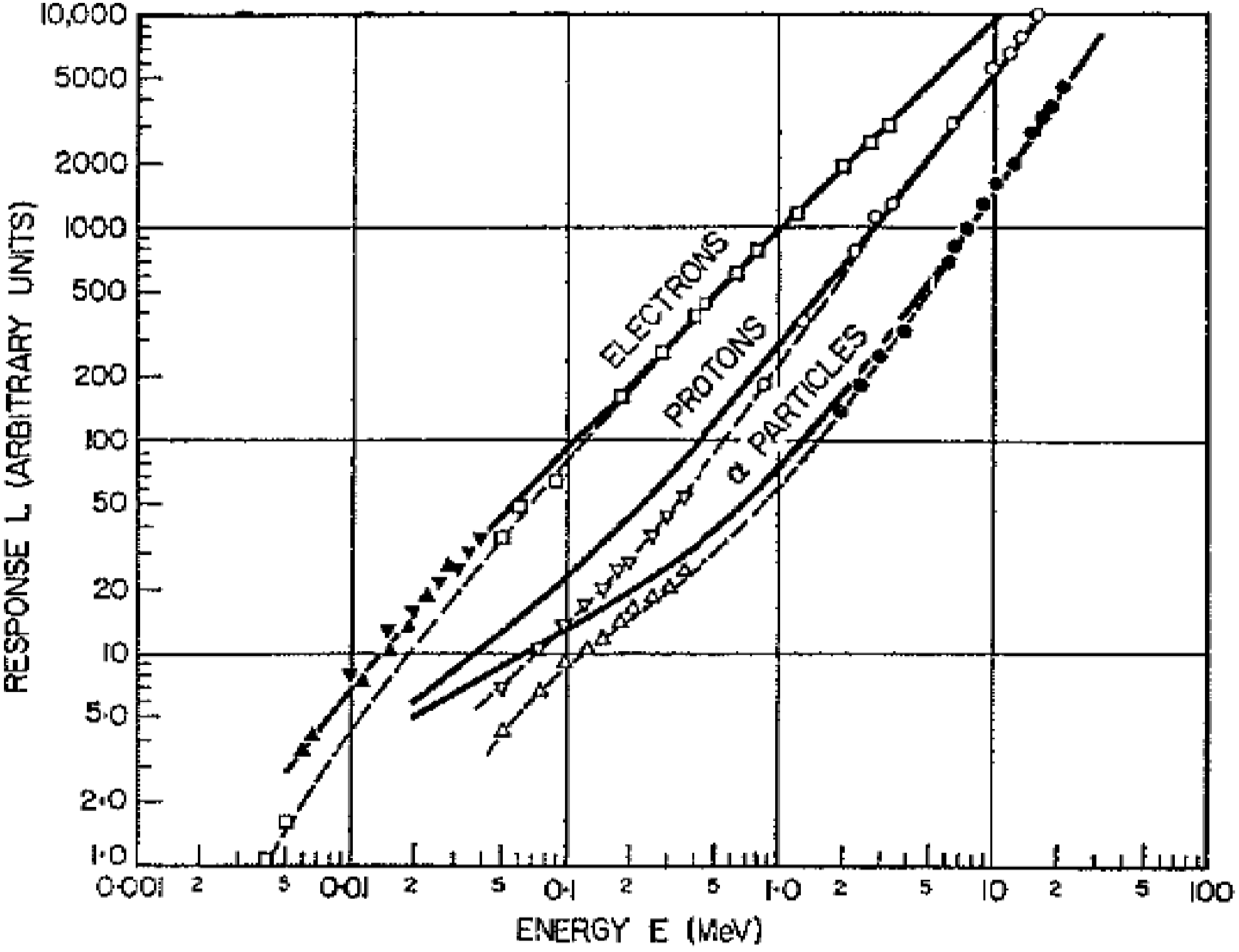
$$W = \frac{E_{abs}}{\langle N_{h\nu} \rangle} = \frac{\langle h\nu \rangle}{S}$$

- With $\langle h\nu \rangle$ ≈ 2-3 eV → W ≈ 100 eV
- S and W strongly depend on the type of incident radiation and sometimes of its energy

Light response of an organic scintillator (3)

- Thus we have → $L = SE_{abs}$
- For particles with small ionization density (electrons with E « not too small » (E > 125 keV) which can be direct e^- or e^- produced by γ) → the distance between 2 successive collisions is large compared to the distance entre 2 neighbouring molecules → the interaction between 2 luminescent sites is thus weak and the response is linear → S is independent on E_{abs}
- The heavy particles (proton, α,…) have a higher ionization and excitation density → the sites are closer and can interact → ↘ of the light emission → S is dependent on E_{abs} → non-linearity (moreover → if the ionization density more ↗ → the limit of the density of the luminescence centers is reached → supplementary ↘ of the response)

Light response of an organic scintillator (4)



Response *L* for anthracene ($C_{14}H_{10}$)

Differential light response of an organic scintillator (1)

- The differential light response of a scintillator *dL/dx* is defined as the fluorescent energy *dL* emitted per unit of distance travelled by the ionizing radiation
- We can wrtite →

$$\frac{dL}{dx} = S\frac{dE_{abs}}{dx}$$

with dE_{abs}/dx the stopping force

- For a small stopping force → the ionizing density is weak → *S* is constant

Differential light response of an organic scintillator (2)

- In a general way → the differential light response follows the law of Birks
- We suppose that the ionization and excitation densities are proportional to the stopping force → $= B\, dE_{abs}/dx$
- We introduce the quenching parameter (or the « ionization quenching ») *k* which is the proportional factor between the fraction of « vanishing » luminescence centers and the ionization density
- Without quenching we have →

$$\frac{dL}{dx} = S_n \frac{dE_{abs}}{dx}$$

with S_n the normal efficiency of the scintillator assumed independent on the energy

Differential light response of an organic scintillator (3)

- By considering the probability of quenching → we obtain the formula of Birks →

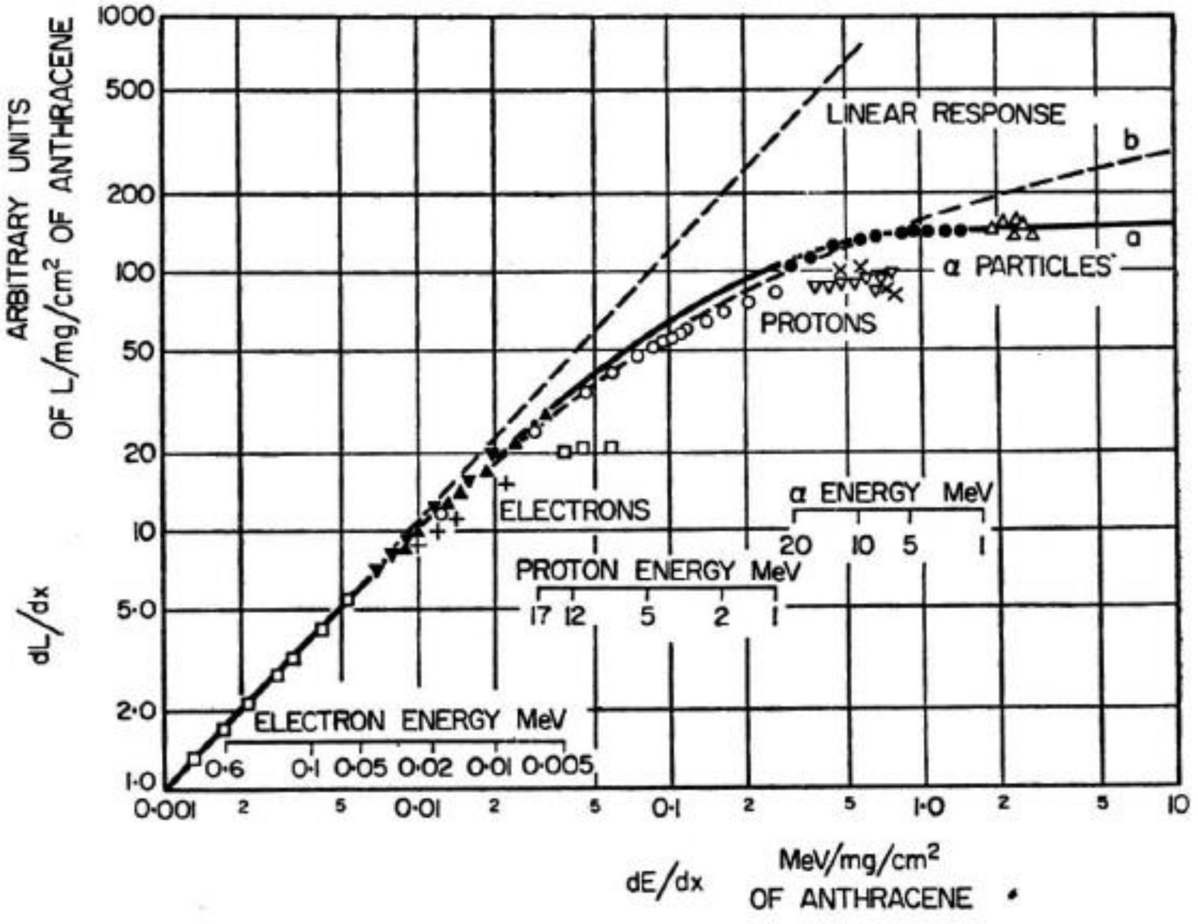
$$\frac{dL}{dx} = \frac{S_n(dE_{abs}/dx)}{1 + kB(dE_{abs}/dx)}$$

- For small dE_{abs}/dx → we find again the expression with neglected quenching
- For large dE_{abs}/dx →

$$\frac{dL}{dx} = \frac{S_n}{kB}$$

- The *kB* parameter is considered as an adjustable parameter allowing a good agreement between theory and experiment

Differential light response of an organic scintillator (4)



Differential light response of anthracene

Time response of an organic scintillator (1)

- The variation of the light intensity as a function of time depends on the population time τ_1 of the luminescence centers and on the lifetime τ of these centers (expression of Hyman)→

$$I = I_0 \left(e^{-t/\tau} - e^{-t/\tau_1} \right)$$

- For prompt plastic scintillators $\tau_1 < \tau$ → example NE111 (« Nuclear Entreprise Technology ») → $\tau_1 = 0.2$ ns and $\tau = 1.7$ ns
- Big advantage of organic scintillators → very prompt response
- We often ignore the population time of the luminescence center → on the other hand at ambient *T* → we cannot neglect the delayed fluorescence due to thermal stimulation

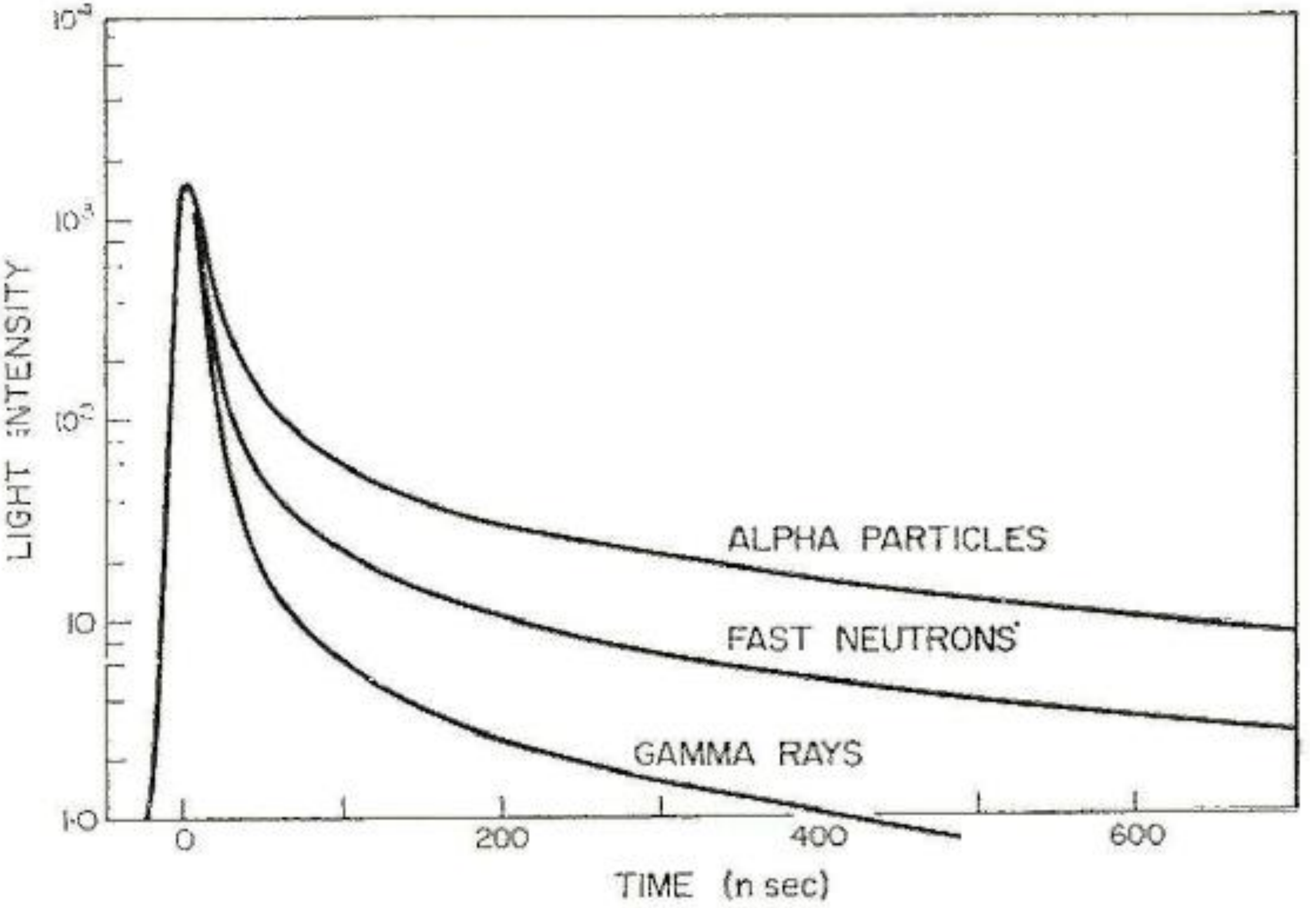
Time response of an organic scintillator (2)

- With τ_r the lifetime of the delayed centers →

$$I = Ae^{-t/\tau} + Be^{-t/\tau_r}$$

- The 2 terms of this expression are called the prompt and slow components of the scintillation → $\tau_r > \tau$
- The slow component implies a long-lived tail in the decay (example → stilbene ($C_{14}H_{12}$) excited by X-rays: $\tau = 6.2$ ns and $\tau_r = 370$ ns)
- τ_r depends on the type of incident particle ↔ on ionization quenching ↔ on the ionization density
- The process of ionization quenching reduces the number of prompt luminescence centers → relative ↗ of the importance of the delayed luminescence

Time response of an organic scintillator (3)



Normalized time responses of the stilbene → possible discrimination as a function of the shape of the pulse

Types of organic scintillators (1)

1. **Pure Crystal**: principally 2 materials → anthracene (the largest scintillation efficiency among all organic scintillators) and stilbene (discrimination as a function of the pulse shape); both are fragilous; a large size is difficult to obtain
2. **Liquid organic solution**: organic scintillator (ex: PBD) dissolved inside an organic solvent (ex: polystyrene) → can have a very important volume; shapes are varied; they are resistant to intense radiations (solids have a structure which can be damaged); they can be mixed to a radioactive solution (liquid scintillation) → the radiation directly crosses the scintillator → large counting efficiency; possible presence dissolved oxygen → decrease of the efficiency of the scintillator; cheap

PBD: 2-phenyl,5-(4-biphenylyl)-1,3,4-oxadiazole → $C_{20}H_{14}N_2O$

Types of organic scintillators (2)

3. **Plastic scintillators** : organic scintillator dissolved into a solvent then polymerization → equivalent to a solid solution (example → styrene (C_8H_8) → polystyrene); ease of fabrication; varied shapes and volumes (very large or very thin → thin films); cheap → very often used
4. **« Loaded » organic scintillators**: due to their small Z → virtually no photoelectric effect for γ → not adapted to γ spectroscopy → addition of lead or tin → enormous decrease of the scintillator efficiency; cheap; rare

Applications of organic scintillators

1. Easily manufactured with varied shapes and volumes and cheap
2. Prompt → lifetime of the fluorescence centers is very small (≈ 2-4 ns) → used for measurement of very small nuclear lifetimes
3. Approximatively linear response for electrons → used for β spectroscopy
4. As liquids → used for the measurement of small activities (^{3}H, ^{14}C sources) → detection efficiency close to 1 for liquid scintillation
5. Large proportion of hydrogen → good detector for fast neutrons (see chapter on neutrons detection)
6. Weak resolution
7. Small Z → not adapted for γ spectroscopy

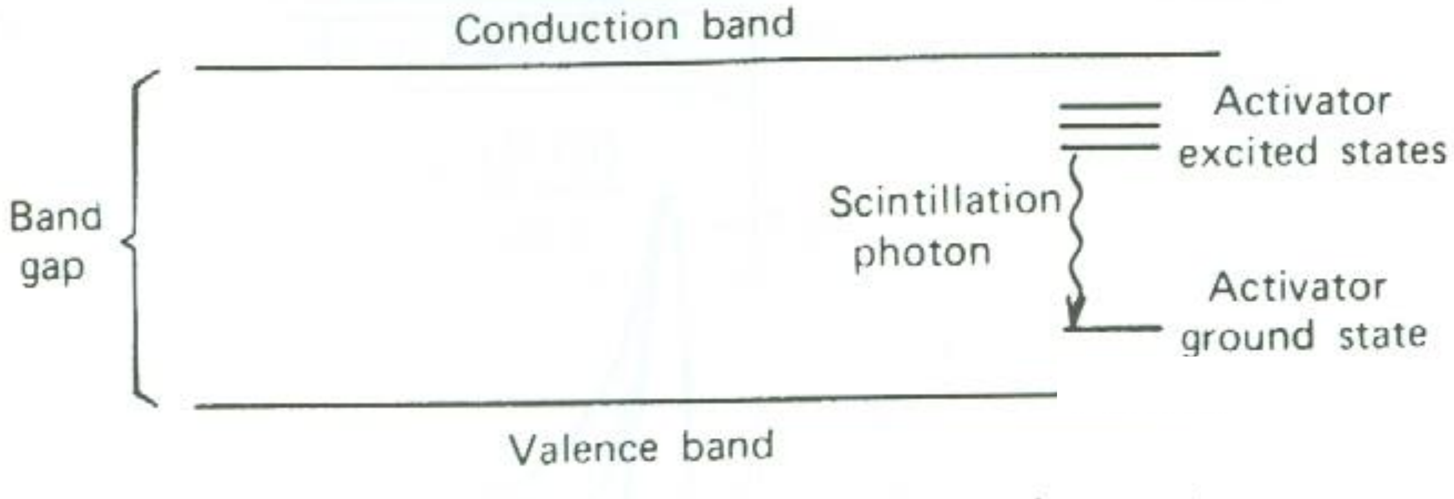
Inorganic scintillators

- Description of inorganic scintillators
- Properties of inorganic scintillators
- NaI(Tl)
- Other inorganic scintillators

Description of inorganic scintillators (1)

- Scintillation mechanism depends on the crystal band structure
- In a pure crystal → absorption of the energy of an incident radiation → production of a large number of e^--h^+ pairs → the e^- are elevated into the conduction band → then transition to the valence band with emission of a photon → inefficient process and generally too high energy for the photon → not in the visible range
- Solution → addition of impurities (activators)

Description of inorganic scintillators (2)

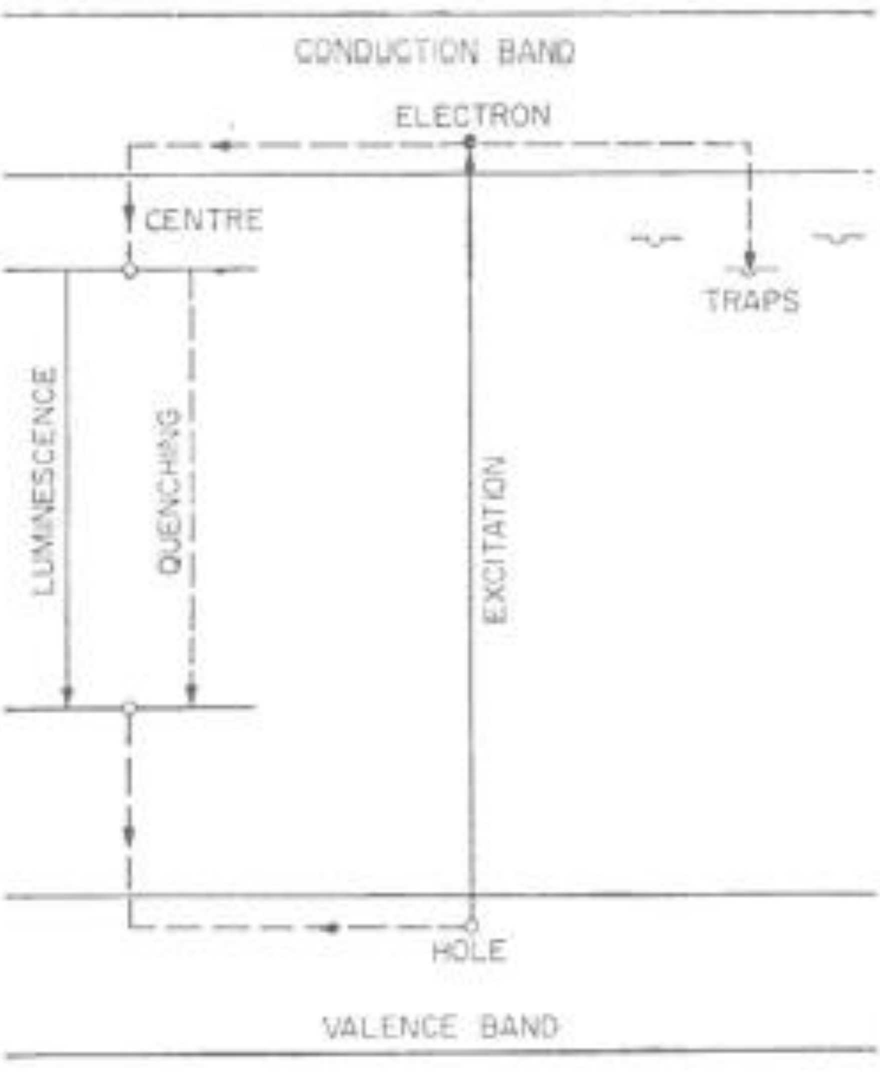


- Addition of impurities → creation of special sites in the lattice → energy band structure modified → energy states within the forbidden gap → the electrons de-excite through these sites called luminescence centers or recombination centers
- Emitted photons have a smaller energy → visible
- Efficiency of the detector ↗

Mechanisms of scintillation (1)

- After the excitation → the h^+ drifts to an activation site and is trapped → creation of a recombination center
- After the excitation → the e^- drifts and ≠ process are possible →
  1. The e^- drifts to a luminescence center → the captured e^- undergoes a transition with photon emission
  2. The e^- drifts to an impurity site for which a transition to the ground state is forbidden → trap → if addition of energy (thermal or optical) → transition to the conduction band and capture by a luminescence center → photon after a longer time (delayed fluorescence)
  3. The e^- is captured by a quenching center = center for which the de-excitation is radiationless → loss mechanism for the conversion of energy into scintillation light
  4. Joint migration of the e^- and h^+ → formation of a bound state (e^--h^+ pair) → exciton → drift of the exciton through the crystal to an impurity center → photon emission

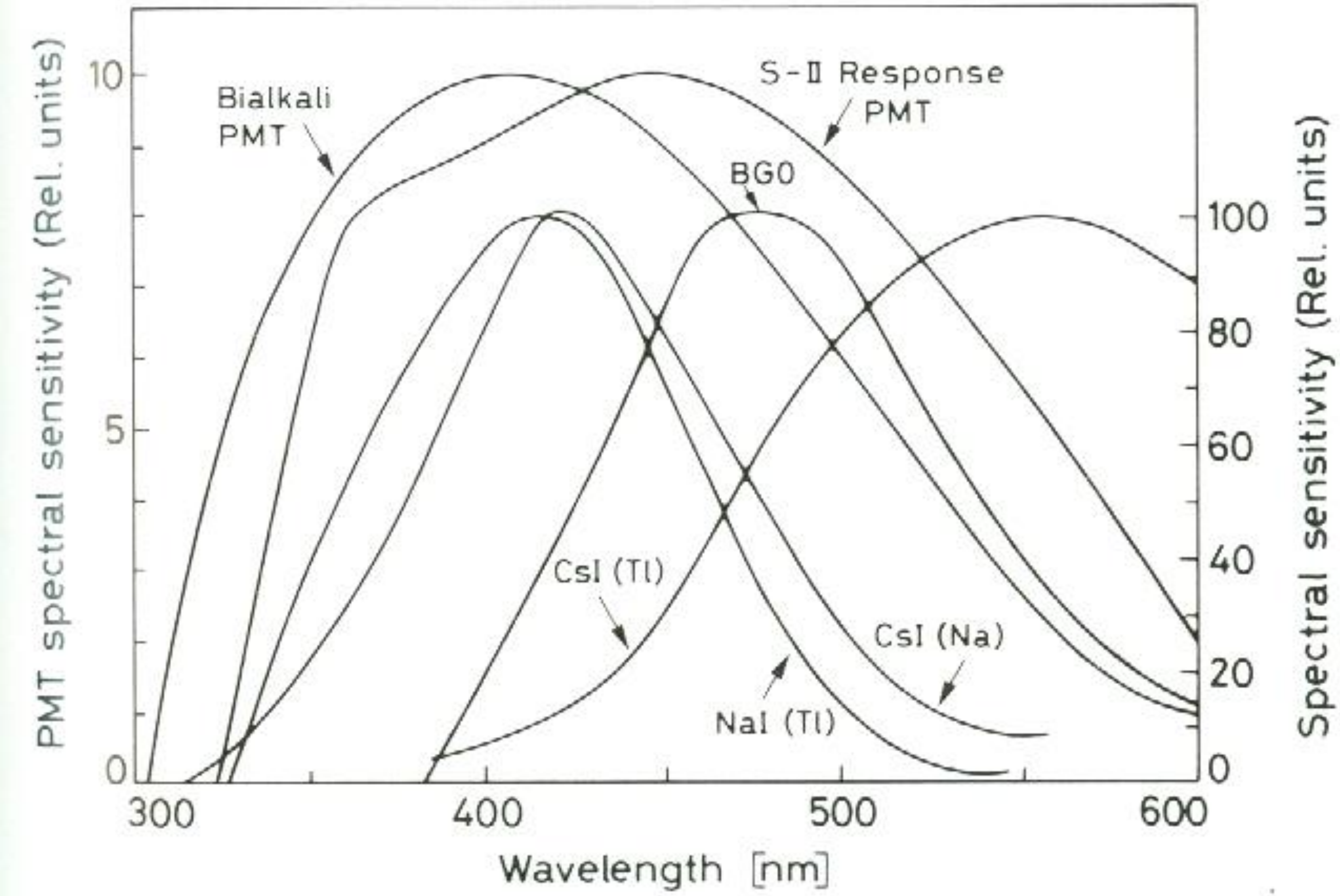
Mechanisms of scintillation (2)



Proprerties of inorganic scintillators (1)

- Typical lifetime of the recombination centers ≈ 50 -500 ns → 2 to 3 orders of magnitude slower than organic scintillators (with a few exceptions) → time evolution described by 1 or 2 exponentials
- Consequence of the luminescence through the activators → liberated energy during luminescence < energy needed to create an e^--h^+ pair → no (or little) superposing of emission and absorption spectra → inorganic scintillator transparent to its scintillation light (without impurity → excitation energy = emitted energy → superposing of the 2 spectra → auto-absorption → to avoid)

Emission spectra

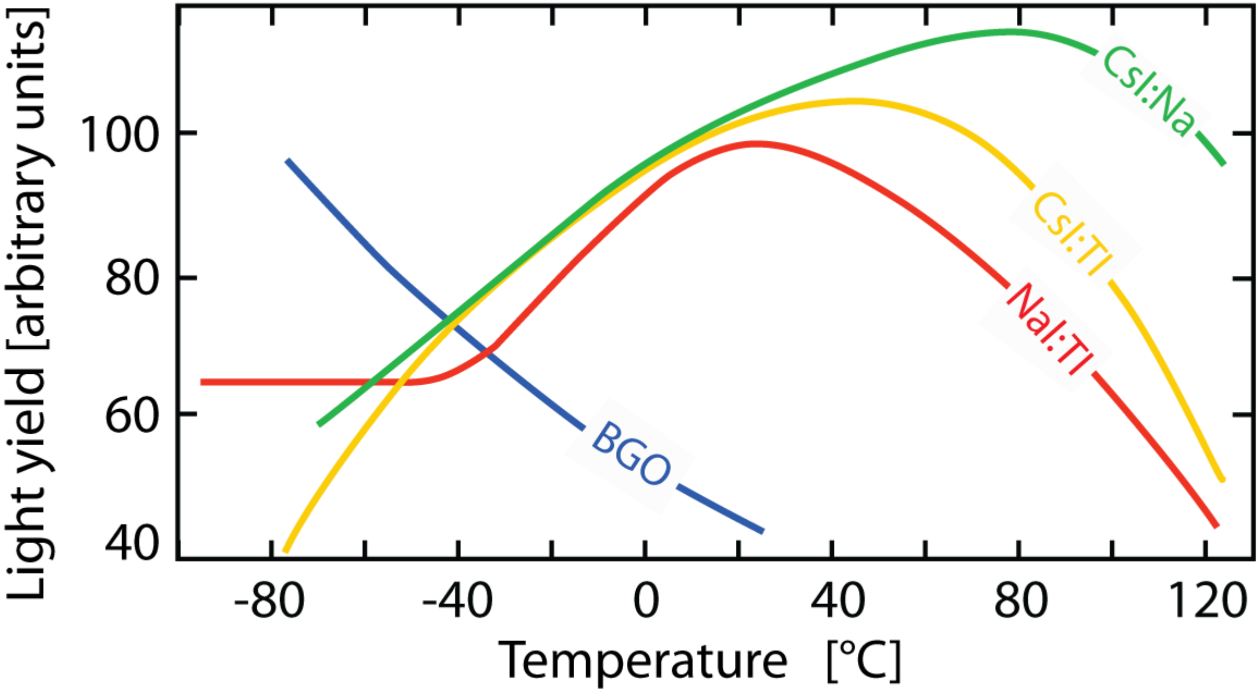


To make full use of the scintillation light → the emission spectrum should fall near the wavelength region of maximum sensitivity of the device used to detect light (ex PM in the figure)

Proprerties of inorganic scintillators (2)

- High density and Z → high stopping force
- High Z → Extremely suitable for γ-rays spectroscopy
- Generally → high luminescence efficiency
- Disadvantage (generally) → highly hygroscopic (absorption of air humidity) → protection against moisture needed
- Particles with high ionization density (proton, α,…) have a higher quenching probability (as for organic scintillators) → presence of non-linearities
- Fano factor $\simeq 1$
- Large variations of the luminescence efficiency as a function of temperature

Temperature dependence

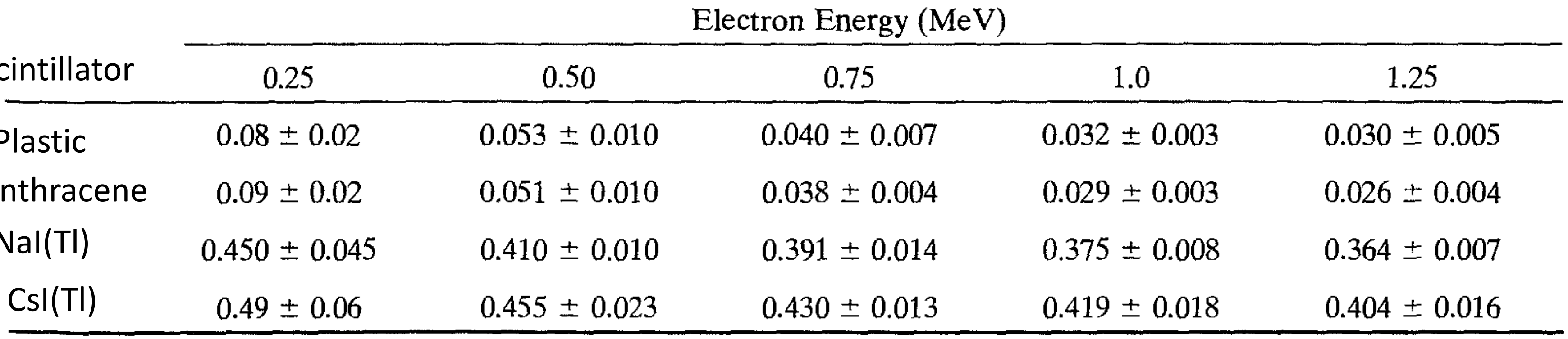


- At small T → the e^- and/or the h^+ are trapped into shallow traps
- When T ↗ → the carriers are liberated and can reach luminescence centers
- When T still ↗ → thermal quenching → ↗ of interactions between molecules and between sites

e^- spectroscopy with a scintillator

- The response of a scintillator (organic or inorganic) to a monoenergetic e^- beam shows a total absorption peak (if the size of the detector is larger than the e^- range) + a queue at small energies due to backscattered e^- (e^- which emerge from the detector by the entrance surface after loosing a part of their energy)
- The effect of backscattering strongly depends on the Z of the medium → Z ↗ → backscattering probability ↗
- Moreover → Z ↗ → Bremsstrahlung ↗ → energy escaping from the detector
- For the e^- spectroscopy → media with small Z are favoured → organic scintillators (conversely media with large Z are favoured for γ spectroscopy)

Examples of backscattering fractions

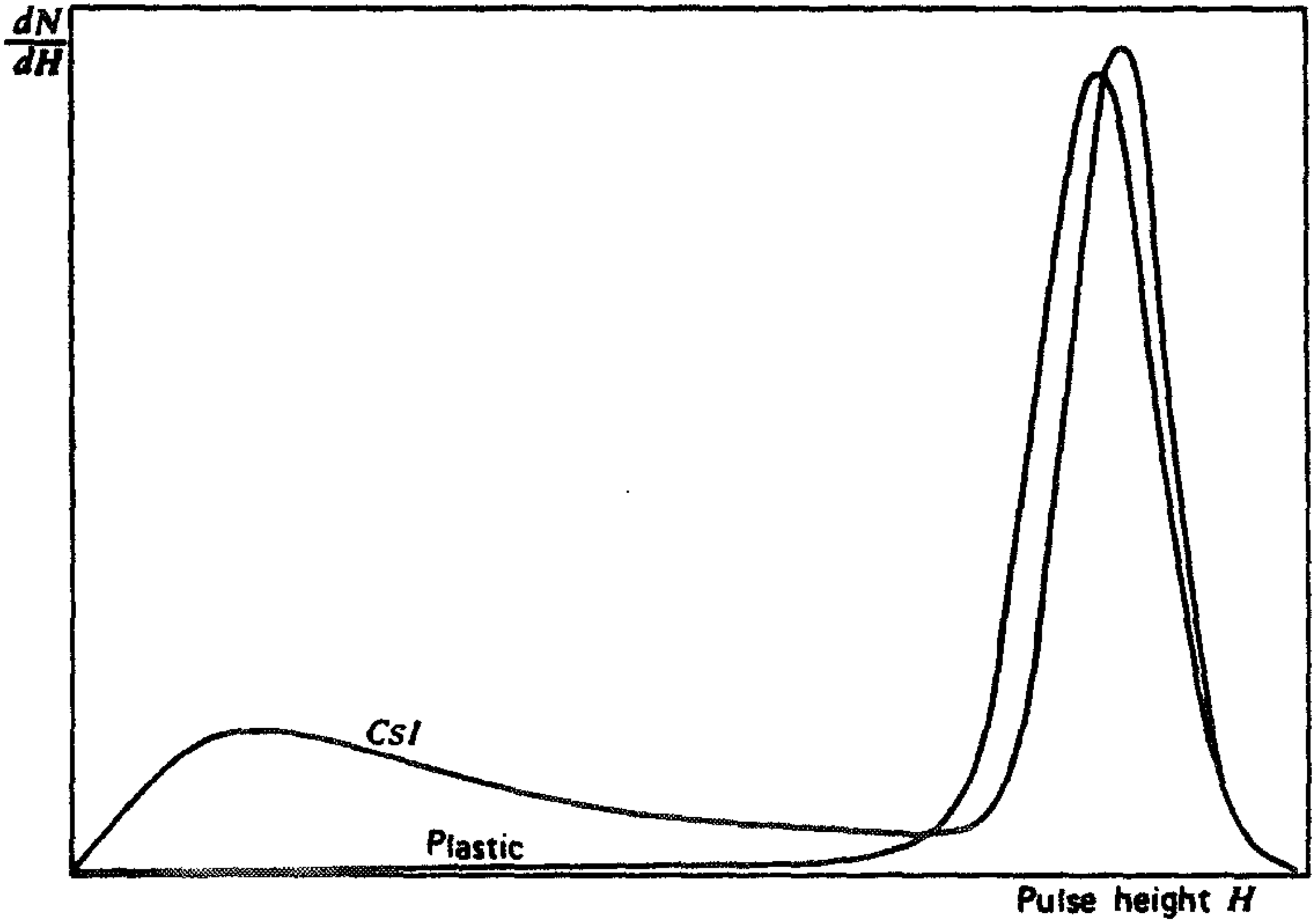


Scintillator	Electron Energy (MeV)				
	0.25	0.50	0.75	1.0	1.25
Plastic	0.08 ± 0.02	0.053 ± 0.010	0.040 ± 0.007	0.032 ± 0.003	0.030 ± 0.005
Anthracene	0.09 ± 0.02	0.051 ± 0.010	0.038 ± 0.004	0.029 ± 0.003	0.026 ± 0.004
NaI(Tl)	0.450 ± 0.045	0.410 ± 0.010	0.391 ± 0.014	0.375 ± 0.008	0.364 ± 0.007
CsI(Tl)	0.49 ± 0.06	0.455 ± 0.023	0.430 ± 0.013	0.419 ± 0.018	0.404 ± 0.016

Fraction of backscattered e^- for a beam normally incident on the scintillator

e^- spectra with a scintillator

1 MeV e^-

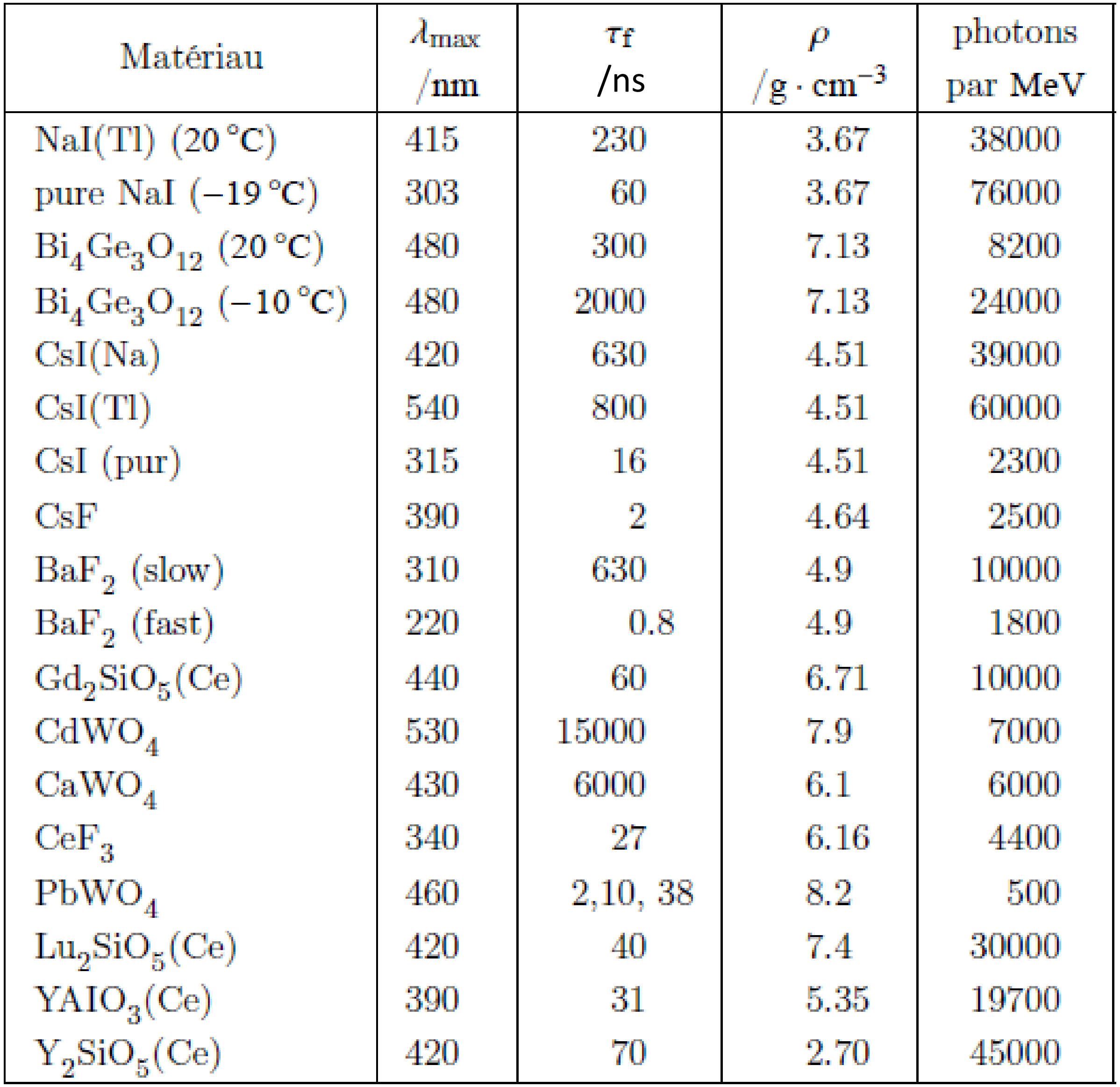


Types of inorganic scintillators

Inorganic scintillators are roughly classified into 3 groups →

1. Scintillators doped by impurities → alkali halides activated by heavy metals (thallium, lead, indium); zinc sulphides activated by copper, manganese, silver;…
2. Non-doped scintillators but auto-activated → there is one component in excess compared to the stoichiometric ratio → ions in excess take an interstitial position → calcium, strontium, cadmium, lead tungstates
3. Pure scintillators → diamond, pure alkali halides

Examples of inorganic scintillators



Matériau	$\lambda_{\max}$ /nm	τ_f /ns	ρ $/\mathrm{g \cdot cm^{-3}}$	photons par MeV
NaI(Tl) (20 °C)	415	230	3.67	38000
pure NaI (−19 °C)	303	60	3.67	76000
$Bi_4Ge_3O_{12}$ (20 °C)	480	300	7.13	8200
$Bi_4Ge_3O_{12}$ (−10 °C)	480	2000	7.13	24000
CsI(Na)	420	630	4.51	39000
CsI(Tl)	540	800	4.51	60000
CsI (pur)	315	16	4.51	2300
CsF	390	2	4.64	2500
BaF_2 (slow)	310	630	4.9	10000
BaF_2 (fast)	220	0.8	4.9	1800
Gd_2SiO_5(Ce)	440	60	6.71	10000
$CdWO_4$	530	15000	7.9	7000
$CaWO_4$	430	6000	6.1	6000
CeF_3	340	27	6.16	4400
$PbWO_4$	460	2,10, 38	8.2	500
Lu_2SiO_5(Ce)	420	40	7.4	30000
$YAlO_3$(Ce)	390	31	5.35	19700
Y_2SiO_5(Ce)	420	70	2.70	45000

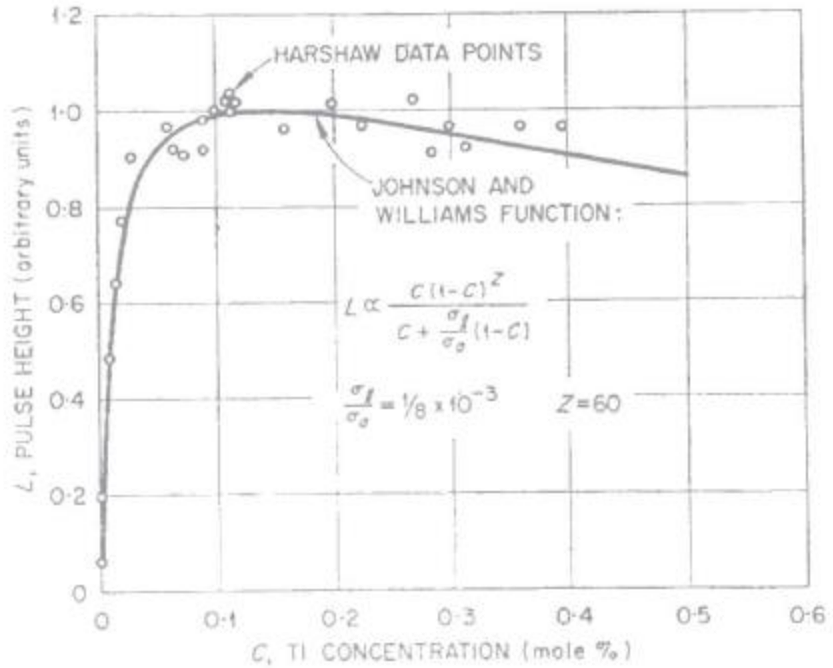
NaI(Tl) (1)

- Sodium iodide crystal activated with thallium
- The use of a NaI crystal for the γ detection has been proposed by Hofstadter in 1948
- High luminescence efficiency, available with various dimensions and shapes
- Most often used scintillator
- Strongly hygroscopic

NaI(Tl) (2)

- Energy band gap for pure NaI: E_g = 6 eV
- NaI(Tl) → emission spectrum centered at ≈ 3 eV
- Concentration of Tl: 0.1%
- Refractive index = 1.85
- For a 1 MeV γ → 38000 photons are created → 26 eV by photon → *E* of 1 photon ≈ 3 eV → *E* emitted as photons ≈ 3 $\times$ 38000 eV = 114000 eV → intrinsic efficiency of the scintillator: S ≈ 11%
- Fano factor *F* = 1
- *W* = 26 eV → high (to be compared to 2.96 eV for Ge) → the bad resolution is one of the principal disadvantages of NaI(Tl)

Efficiency of NaI(Tl) as a function of Tl concentration

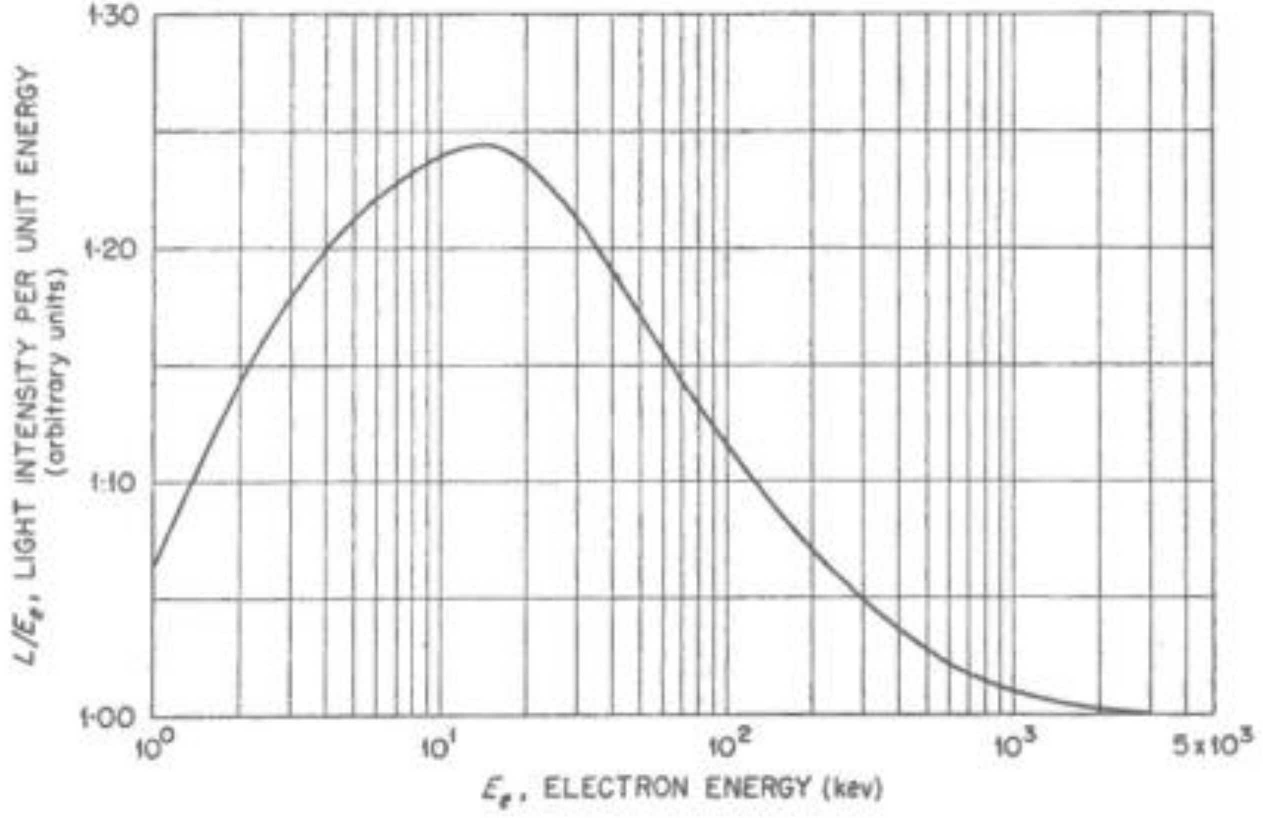


When the Tl concentration too much ↗ → interaction between the recombination sites → quenching → efficiency ↘

Intrinsic efficiency of NaI(Tl) (1)

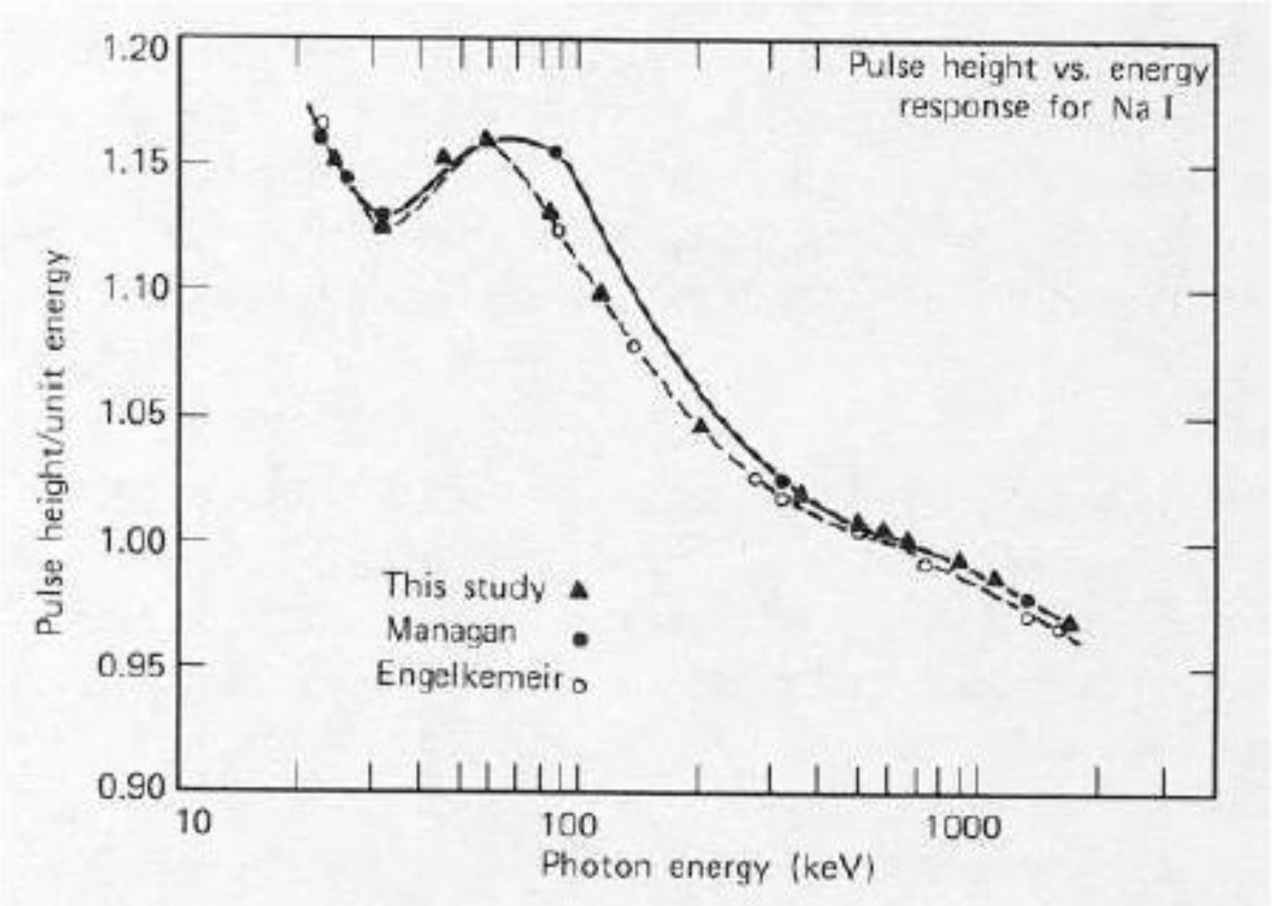
- The intrinsic efficiency of NaI(Tl) $S = L/E$ should be constant as a function of the incident radiation energy to have a linear process
- As for e^- or γ → it is not the case → the difference can reach 15%
- No convincing explanation for this phenomenon as a whole

Intrinsic efficiency of NaI(Tl) (2)



For incident e^-

Intrinsic efficiency of NaI(Tl) (3)



For incident γ

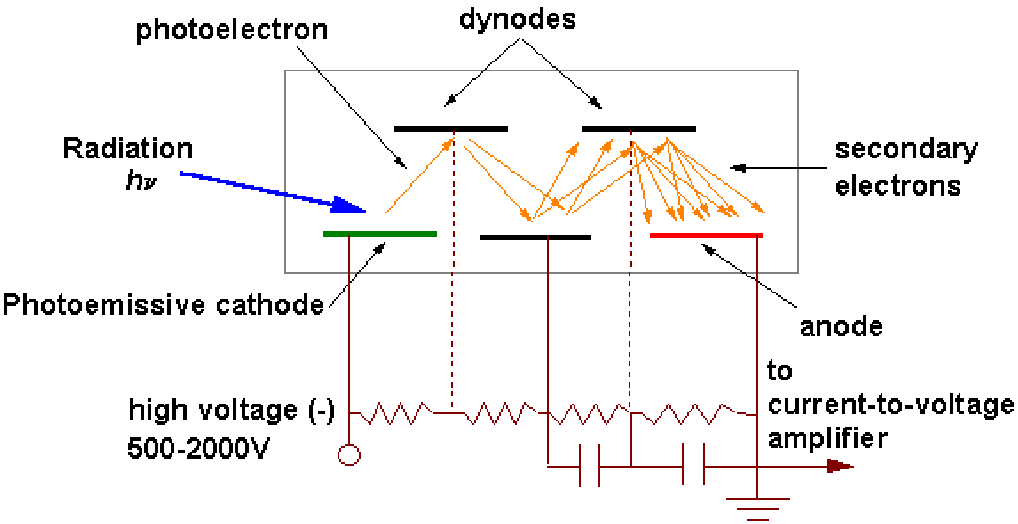
Other inorganic scintillators (1)

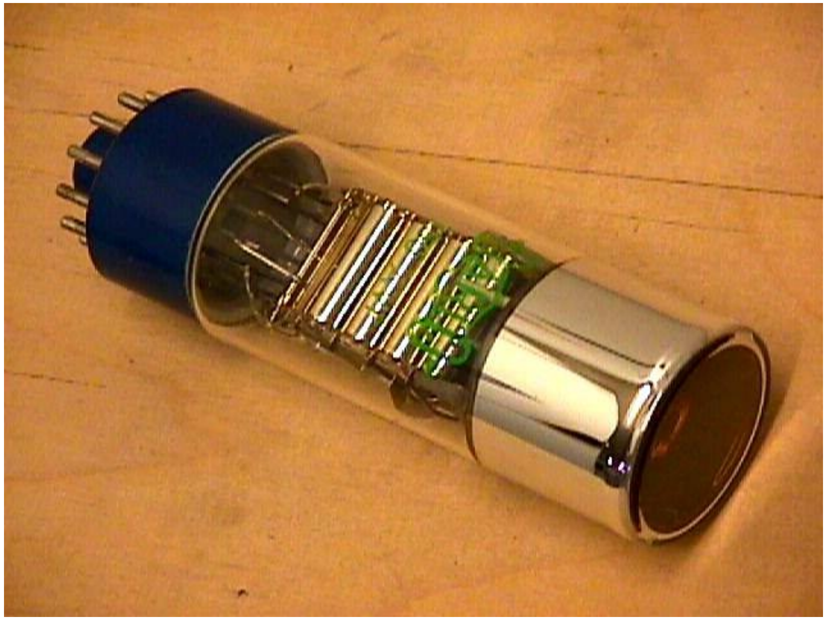
- Cesium iodide doped with thallium - CsI(Tl):
  - Absorption probability of a γ larger than the NaI(Tl) → important for instance for space instrumentation for which weight and size are very important
  - The slow component of the decrease strongly depends on the type of incident particle → discrimination as a function of the shape of the pulse
  - Less fragile than NaI(Tl)
  - Reasonably malleable
  - Maximum of the emission spectrum shifted to the large wave lengths → less adapted to the coupling with a photomultiplier
- Bismuth germanate - $Bi_4Ge_30_{12}$ (or BGO):
  - More dense (7.13 g cm^{-3}) than NaI and high Z of Bi ($Z = 83$) → particularly adapted to γ spectroscopy
  - Robust detector
  - Easy to manufacture
  - Small luminescence efficiency → 10-20% of the efficiency of NaI(Tl)

Other inorganic scintillators (2)

- Cadmium tungstate - $CdWO_4$:
  - Weak luminescence efficiency → 40% of the efficiency of NaI(Tl)
  - Time decrease is double and extremely slow → 1.1 and 14.5 μs → use limited to weak counting rates but good discrimination as a function of the pulse shape
  - Good resolution
  - High refractive index (2.3) → difficult coupling to the photomultiplier
- Barium Fluoride - BaF_2:
  - Lifetime of the luminescence centers extremely short (0.6 ns) → to use when a rapid response is required
  - Short emission wave lengty → necessary coupling with a sensor sensitive to UV
  - Weak luminescence efficiency → 20% of the efficiency of NaI(Tl)
- Lithium iodide doped with europium - LiI(Eu):
  - Neutrons detection (see chapter on neutrons)

Photomultiplier (PM)





Principles of the photomultiplier

- Goal of the PM → conversion of the energy of a (close to) visible radiation into electric energy → use of photoemission phenomenon and then amplification thanks to secondary emission process
- PM = glass vessel in which there is vacuum
- The incident photons penetrate into the PM and hit a semi-transparent or opaque photocathode → interaction of the photon with the atoms of the photocathode → possible ejection of an e^- out of the photocathode
- The photoelectrons stemmed from the photocathode are accelerated by an electric field and hit the 1st dynode → due to secondary emission process → secondary e^- are ejected out of the 1st dynode and then accelerated to the 2nd dynode → new secondary e^- which are accelerated … → process which is repeated until the e^- go out the last dynode and are collected by the anode → signal

Photocathode (1)

- If the photocathode is opaque → the e^- are emitted from the photon entrance surface
- If it is very thin (semi-transparent) → the e^- can leave from the surface opposite from the photon entrance surface
- This thin configuration mince is adopted most of the time → it facilitates both the optic coupling with the external light source and the electronic coupling of the photocathode with the first dynode

Photocathode (2)

1. A photon have to cross the entrance window (depth *e*) of the PM → probability $T(\lambda,e)$
2. A photon with λ wavelength incident on a medium can be reflected, absorbed or transmitted → with ρ, α and τ the probabilities associated with these 3 processes →

   $$\rho(\lambda) + \alpha(\lambda) + \tau(\lambda) = 1$$

   → the photon has to get into the photocathode → its material must have a low reflection coefficient
3. The photon which is gone into the photocathode must be absorbed there → transfer of its energy to an electron → with $\mu(\lambda)$ the absorption probability per length unit → the probability p_{abs} to have a photon absorption at a depth *x* inside the interval *dx* is →

   $$p_{abs}(x)dx = e^{-\mu(\lambda)x}\mu(\lambda)dx$$

Photocathode (3)

If we consider a normal incidence on the material with depth *d* → the integration of p_{abs} from 0 to *d* gives →

$$\alpha(\lambda, d) = [1 - \rho(\lambda)]\left(1 - e^{-\mu(\lambda)d}\right)$$

4. The electron is moving inside the material → it undergoes collisions → it loses energy → it possibly arrives at the surface between the material and the vacuum → the material must have a large escape depth (e^- origin depth such it can reach the surface with enough energy)
5. Thee$^-$ must escape from the photocathode → its energy must be > than the work function Φ of the photocathode

Photocathode (4)

- We define the photoelectric quantum efficiency $\eta_{ph}(\lambda)$ →

$$\eta_{ph}(\lambda) = \frac{\text{number of e}^{-}\text{ emitted by the photocathode}}{\text{number of photons absorbed by the photocathode}}$$

- We also define the spectral quantum efficiency $\eta(\lambda)$ →

$$\eta(\lambda) = \frac{\text{number of e}^{-}\text{ emitted by the photocathode}}{\text{number of photons entering into the PM}}$$

- We have thus → $\eta(\lambda) = T(\lambda, e)\alpha(\lambda, d)\eta_{ph}(\lambda)$
- We also define the effective quantum efficiency η_{eff} of a photomultiplier which receives a light with the $I(\lambda)$ spectrum →

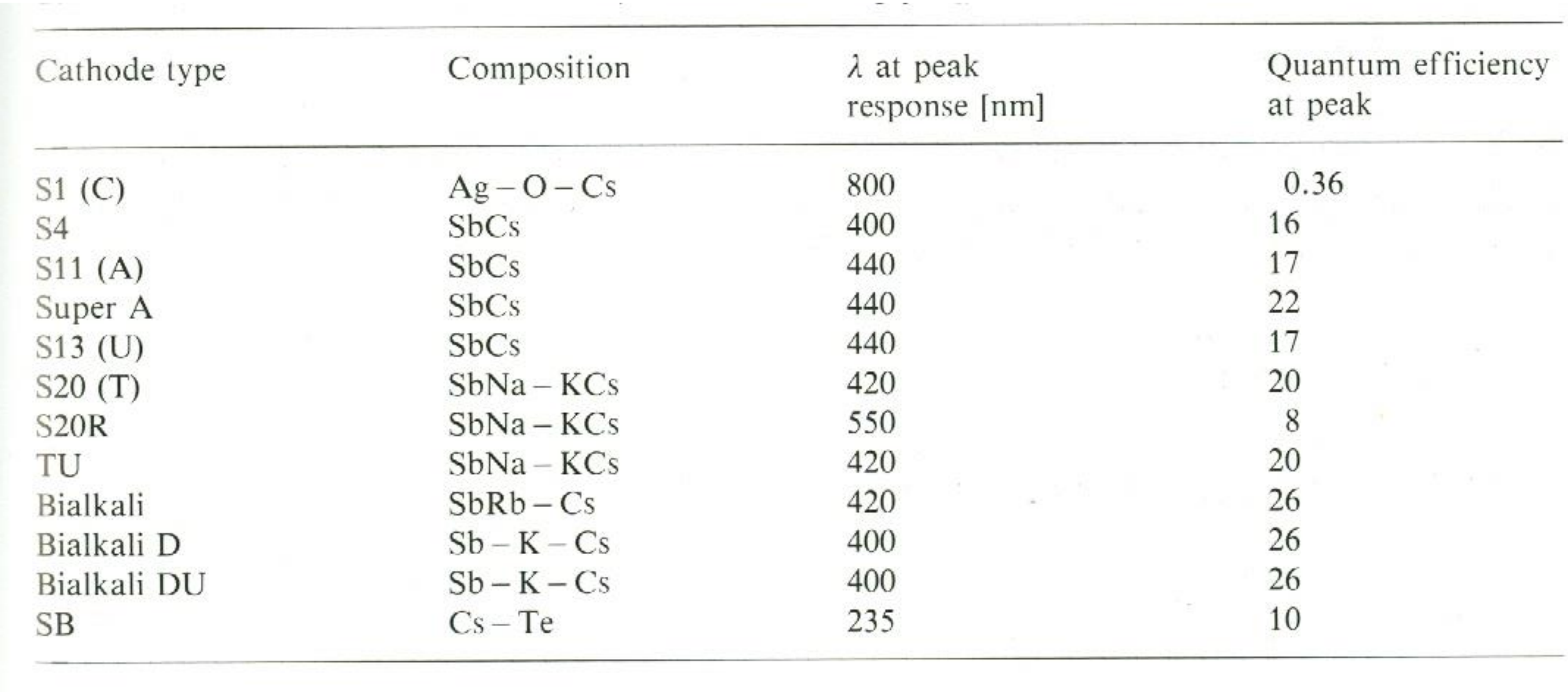
$$\eta_{eff} = \int_0^\infty I(\lambda)\eta(\lambda)d\lambda$$

Choice of the material for the photocathode

- Metals are characterized by a large reflection probability, a small escape depth (because of the large number of free e^- inside a metal) and a high work function → small quantum efficiency ($\eta(\lambda) < 0.1\%$)

- Semiconductors have a small reflection probability, a escape depth (small amount of free e^-) and a small et une work function → $\eta(\lambda) \approx 10\text{-}30\%$

Examples of photocathode materials



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

Photocathode noise

- The photocathode spontaneously emits electrons due to thermionic emission → at ambient T → this emission is responsible of most of the part of the PM noise
- The number of emitted electrons by unit of time and surface is given by Richardson's law:

$$\eta_e = AT^2 \exp -e\Phi/kT$$

with A: constant, T: temperature, k: Boltzmann's constant

- As Φ is smaller for a sc than for a metal → η_e is larger for a sc (≈ 10^2-10^4 $s^{-1}cm^{-2}$) than for a metal (≈ 10^{-2} $s^{-1}cm^{-2}$)
- If T↘ η_e ↘ but other noise sources exist (ionization of residual gas inside the PM, radioactivity of the glass constituting the PM, cosmic rays,…)

Dynodes

- In dynode, electron energy is transferred to dynode electrons → a certain number of electrons can escape (again semiconductors are used) → gain of each dynode: secondary emission factor δ ($\delta > 1$ to have multiplication)

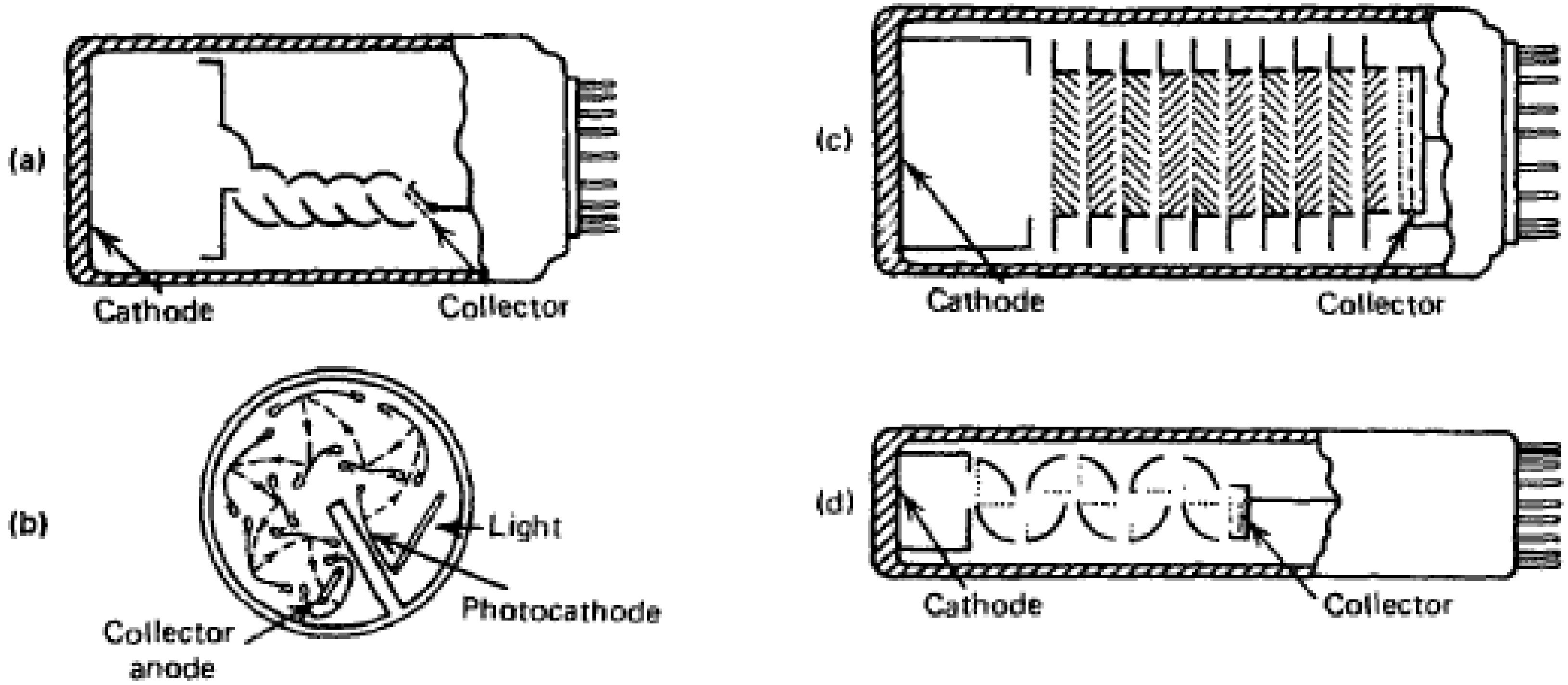
- Constant electric field is maintained between dynodes to accelerate and guide electrons → the secondary emission material must be deposited on a conducting material

- The gain of the PM: $M = \delta^n$ with $n \approx 10$ to obtain $M = 10^7$

PM gain

- If each electron hitting a dynode eject ≈ 4 electrons → the gain of a PM with 12 stages (or dynodes) is $M = 4^{12} \approx 1.7 \times 10^7$
- Only one photoelectron produces 17 millions electrons
- All these electrons arrive (quasi) simultaneously at the anode → $t <$ 5 ns
- The current pulse at the anode is ≈ 0.5 mA

Different types of PM (1)



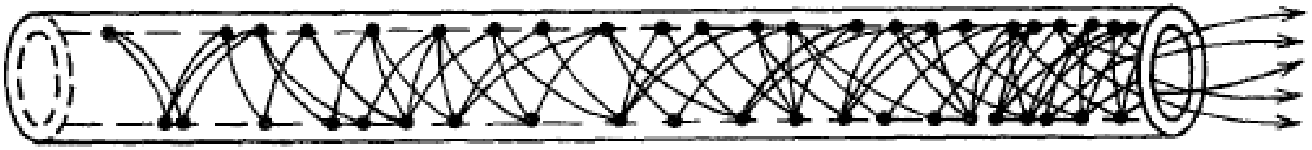
a) Focused linear structure
b) Circular grid
c) Venetian blind
d) Box-and-grid

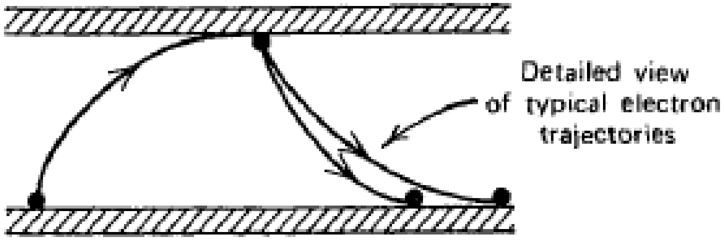
Different types of PM (2)

- Structures (a) and (b) use an electron focalization between dynodes → the electron transit time through the structure is speeded up compared to other structures → fast PM
- The structures (c) and (d) have a better collection efficiency from the photocathode at the first dynode than structures (a) and (b)
- The Venetian blind type (c) is the oldest and shows a slow response time because of the low electric field → obsolete
- The structure (d) is also fairly old and slow but it is still standard in many tubes of large diameter

Different types of PM (3)

- Continuous channel electron multiplier → "continuous chain of dynodes"
- The electric potential linearly varies along the tube → an incoming electron produces secondary electrons that are accelerated until they in turn produce further secondaries
- We finally have a large number of electrons at the end of the tube





Resolution of a scintillation detector (1)

- Scintillation detector = scintillator + PM
- By considering *C* the probability for a photoelectron to reach the 1st dynode, N_0 the number of electrons collected at the anode and N_{ph} the number of photons emitted inside the scintillator →

$$N_0 = MC\eta N_{ph}$$

- N_0 is thus $\propto$ to the energy E_{abs} absorbed inside the detector (via N_{ph})
- All these quantities are random variables → calculation of the variance
- By considering $v[X]$ the relative variance of the random variable X →

$$v[X] = \frac{\sigma^2(X)}{\langle X \rangle^2}$$

Resolution of a scintillation detector (2)

- We have thus for $v[N_0]$ →

$$\begin{aligned}
v[N_0] &= v[N_{ph}] + \frac{1}{\langle N_{ph}\rangle} v[\eta] + \frac{1}{\langle N_{ph}\rangle\langle\eta\rangle} v[C] + \frac{1}{\langle N_{ph}\rangle\langle\eta\rangle\langle C\rangle} v[M] \\
&= \left(v[N_{ph}] - \frac{1}{\langle N_{ph}\rangle}\right) + \frac{1}{\langle N_{ph}\rangle}\left(v[\eta] - \frac{1-\langle\eta\rangle}{\langle\eta\rangle}\right) \\
&\quad + \frac{1}{\langle N_{ph}\rangle\langle\eta\rangle}\left(v[C] - \frac{1-\langle C\rangle}{\langle C\rangle}\right) + \frac{1}{\langle N_{ph}\rangle\langle\eta\rangle\langle C\rangle}(1 + v[M])
\end{aligned}$$

- If N_{ph} is a Poisson variable and C and η are binomial →

$$v[N_0] = \frac{1}{\langle N_{ph}\rangle\langle\eta\rangle\langle C\rangle}(1 + v[M]) \propto \frac{1}{E_{abs}}$$

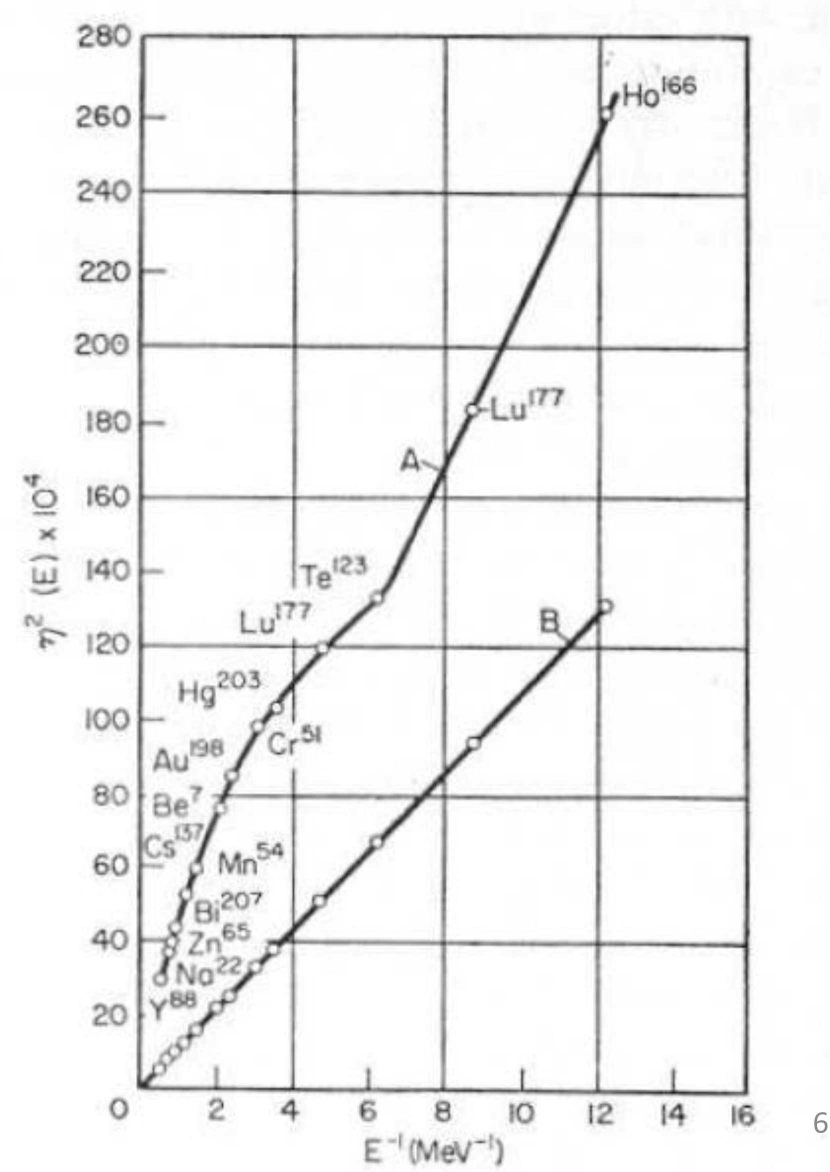
Resolution of a scintillation detector (3)

- As 1st approximation → The relative variance on $N_0 \propto 1/E_{abs}$

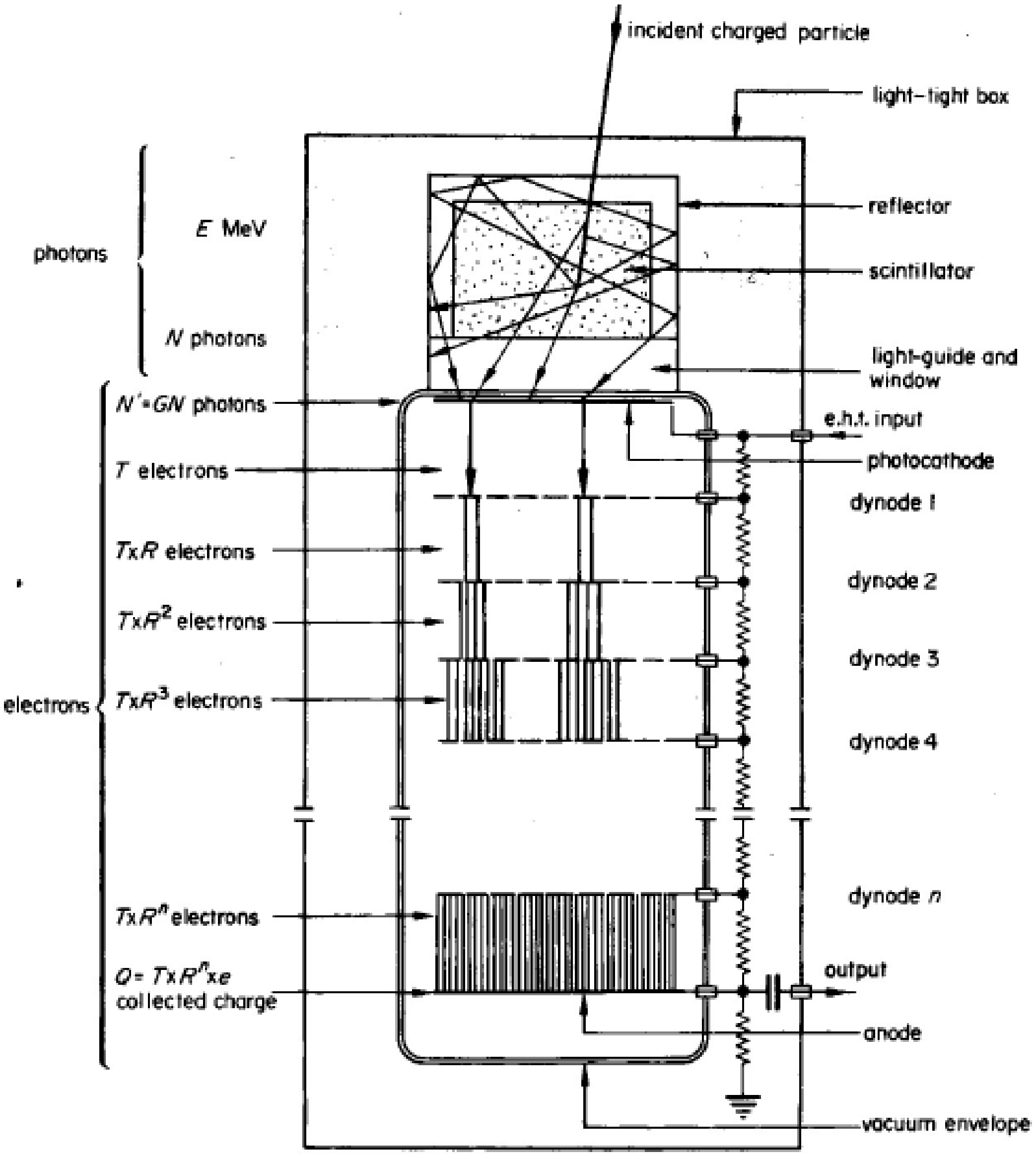
- However → many non-linear effects are present:
  - The number of photons escaping from the scintillator depends on their emission position → N_{ph} withdraws from a Poisson variable
  - Inhomogeneity in the photocathode → η withdraws from a binomial
  - Collection efficiency of the photoelectrons by the 1st dynode depends on the emission position → C withdraws from a binomial

Resolution of a scintillation detector (4)

- Resolution of a NaI(Tl) detector associated to a PM
- Curve B → resolution by only considering the PM → $\propto$ $1/E_{abs}$
- Curve A → total resolution → discrepancy by comparison to the $1/E_{abs}$ law



γ spectroscopy with a NaI(Tl) (1)



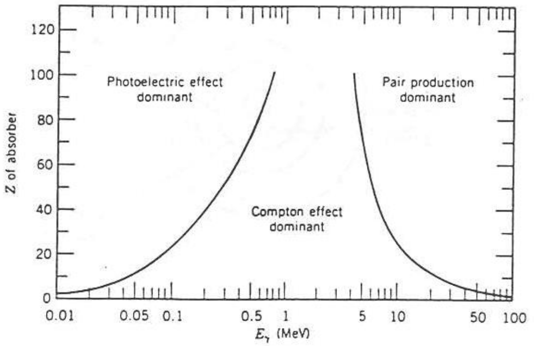
γ spectroscopy with a NaI(Tl) (2)

Caution: Size of detector is crucial!! ↔ size must be compared with mean free path of secondary γ rays produced in interactions of the original γ rays (Compton scattered γ rays and annihilations photons formed at the end of the track of e^+ created in pair production) → mean free path of these secondary γ rays is ≈ 3-5 cm in NaI → « small » means ≈ 1 cm and « large » means ≈ 30 cm

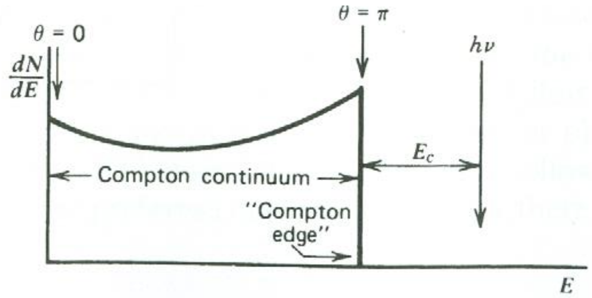
In the following, we consider « intermediate » size for the detector → classicaly: NaI(Tl) 3"x3" (1 inch=2.54 cm) → diameter = length = 7.62 cm

Photons with hν = 1 MeV

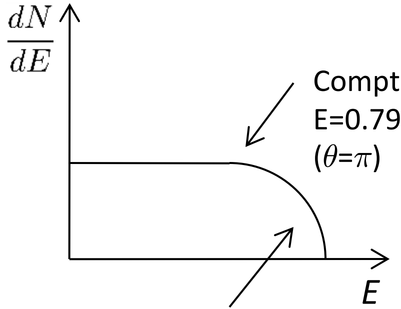
- Dominant process: Compton scattering



- We suppose that all photons have exactly 1 Compton scattering before escaping



- We suppose that all photons have *n* Compton scatterings before escaping (time history small compared to the detector response)

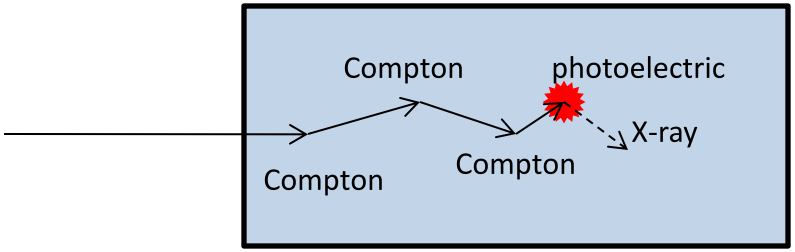


Compton edge
E=0.796 MeV
(θ=π)

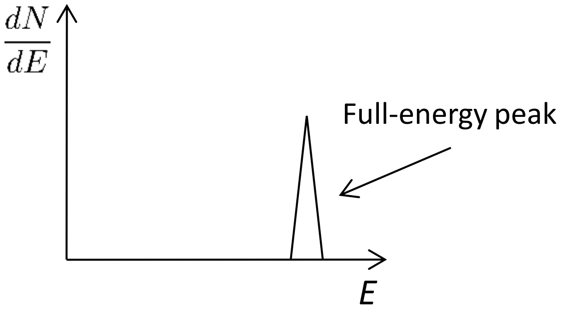
Multiple Compton events

Photons with hν = 1 MeV (2)

- After *n* Compton scatterings → E ↘ (E_n) → photoelectric effect becomes dominant (we suppose it always occurs) → E_n-B_K is absorbed

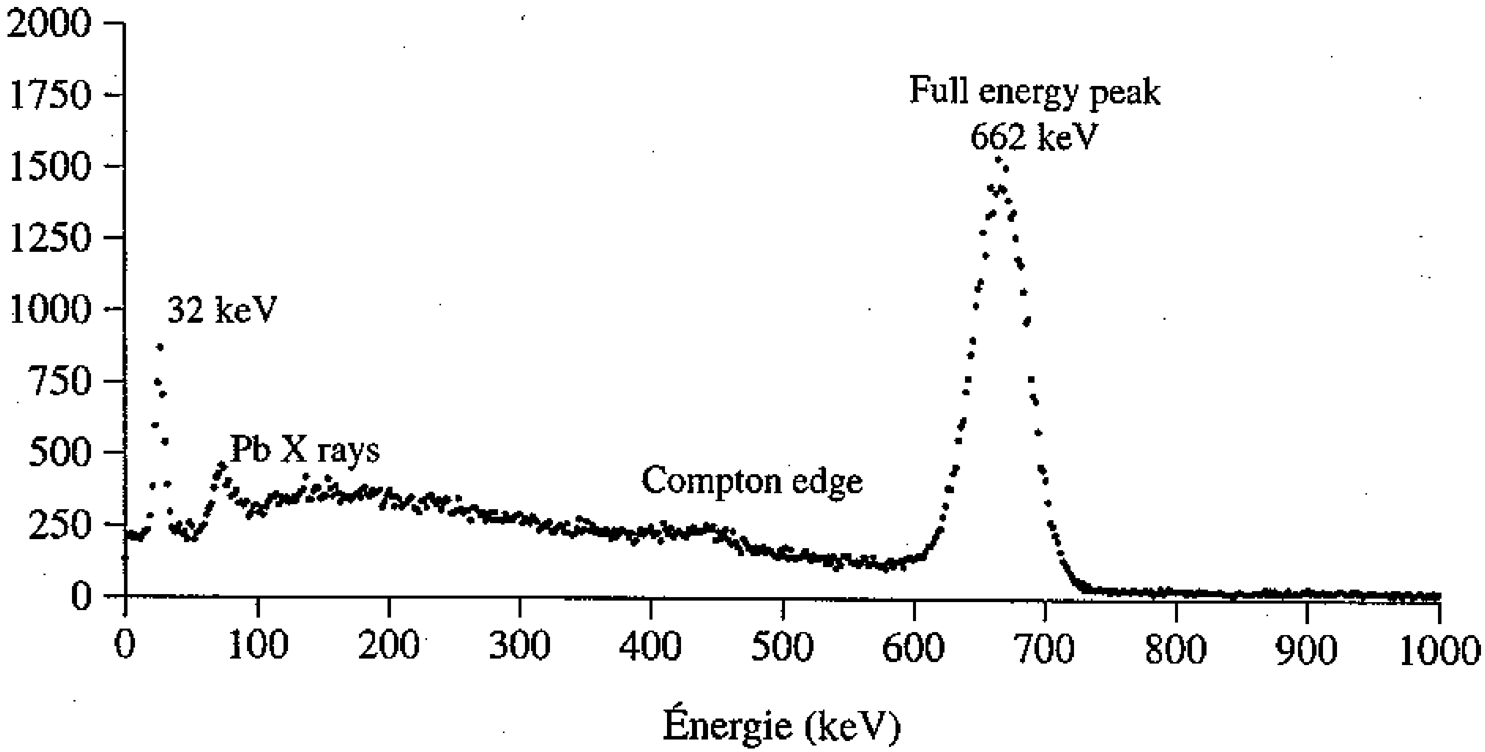


- As photoelectric effect occurs deep inside the detector → X-rays or Auger electrons cannot escape → energy B_K is deposited (again time history small compared to the detector response)



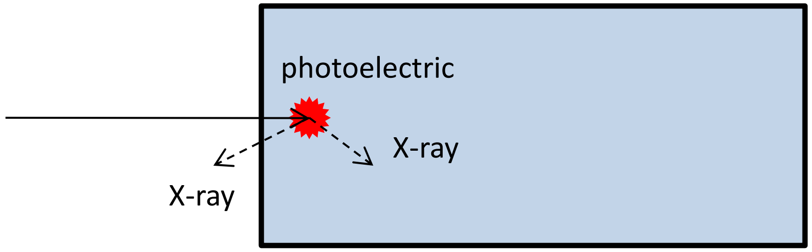
Photons with hν = 1 MeV (3)

- Practically, photon can escape after a few Compton scattering or can be absorbed → example of ^{137}Cs (662 keV γ):

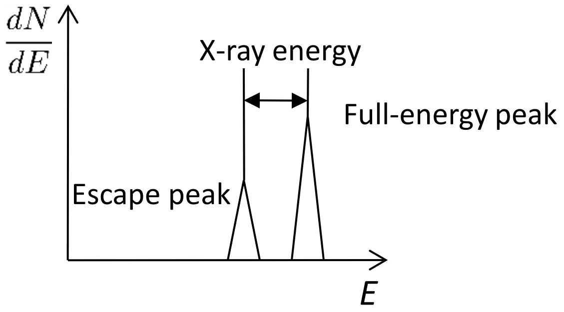


Photons with hν = 100 keV

- Dominant process: Photoelectric absorption

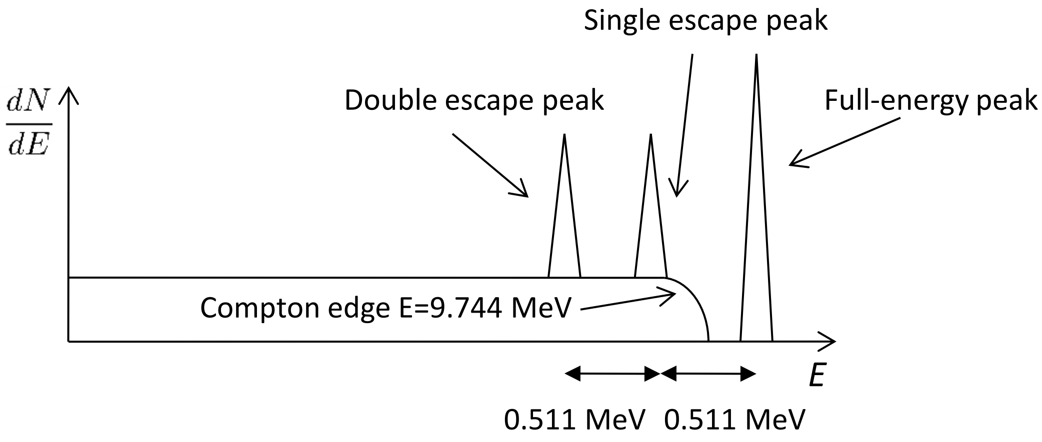


- X-ray ($E = B_K - B_L$) can escape (absorption occurs close to the entrance) →



Photons with hν = 10 MeV

- Compton or pair creation → if pair creation → deposited energy = hν-2m$_e$c^2 (m$_e$c^2 = 0.511 MeV) → both γ of 0.511 MeV can escape or one γ can escape or both γ can be detected (Compton or photoelectric)



Complications in the response function (1)

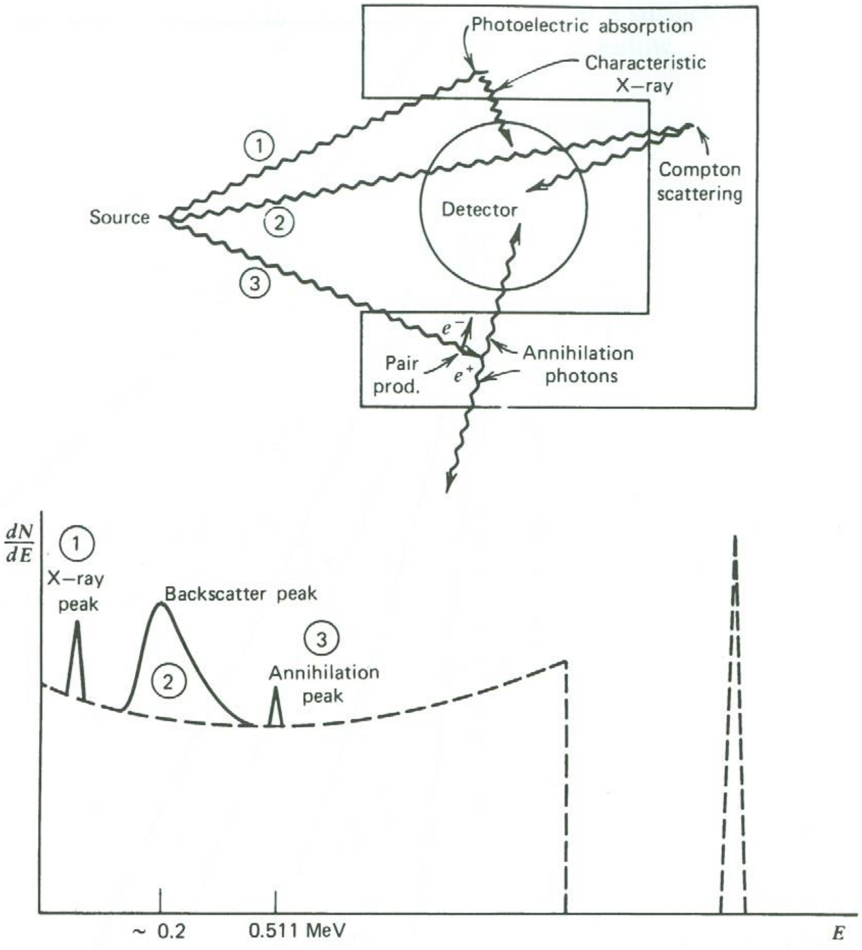
- Secondary radiations created near the source:

  1. Annihilation radiation: if source emits e^+ → an additional 0.511 MeV peak will be measured due to the annihilation in the material encapsulating the source
  2. Bremsstrahlung: γ –ray emitters are generally also β emitters → to avoid energy deposition from these β in detector → they are stopped by encapsulating material or be an absorber before the detector → but generation of Bremsstrahlung (complex to precisely study) → to avoid this Bremsstrahlung radiation → β absorber must have small Z

Complications in the response function (2)

- Effect of surrounding materials

1. X-ray peak from the surrounding material
2. Backscattered γ rays in the vicinity of 0.2-0.25 MeV
3. Annihilation peak due to e^+ from the surrounding material



Comparison germanium/scintillators for γ spectroscopy

- Ge: Much better resolution but

- Expensive
- Small detector size and low Z → ratio full-energy peak/background largely smaller
- Slower
- Complication of cryogenics (not with modern detectors)

Example of comparison: ^{110m}Ag