SCINTILLATORS AND SILICON PHOTOMULTIPLIERS

PHD PHYSICS COURSE – XXXIII CYCLE

UNIVERSITÀ DI BARI

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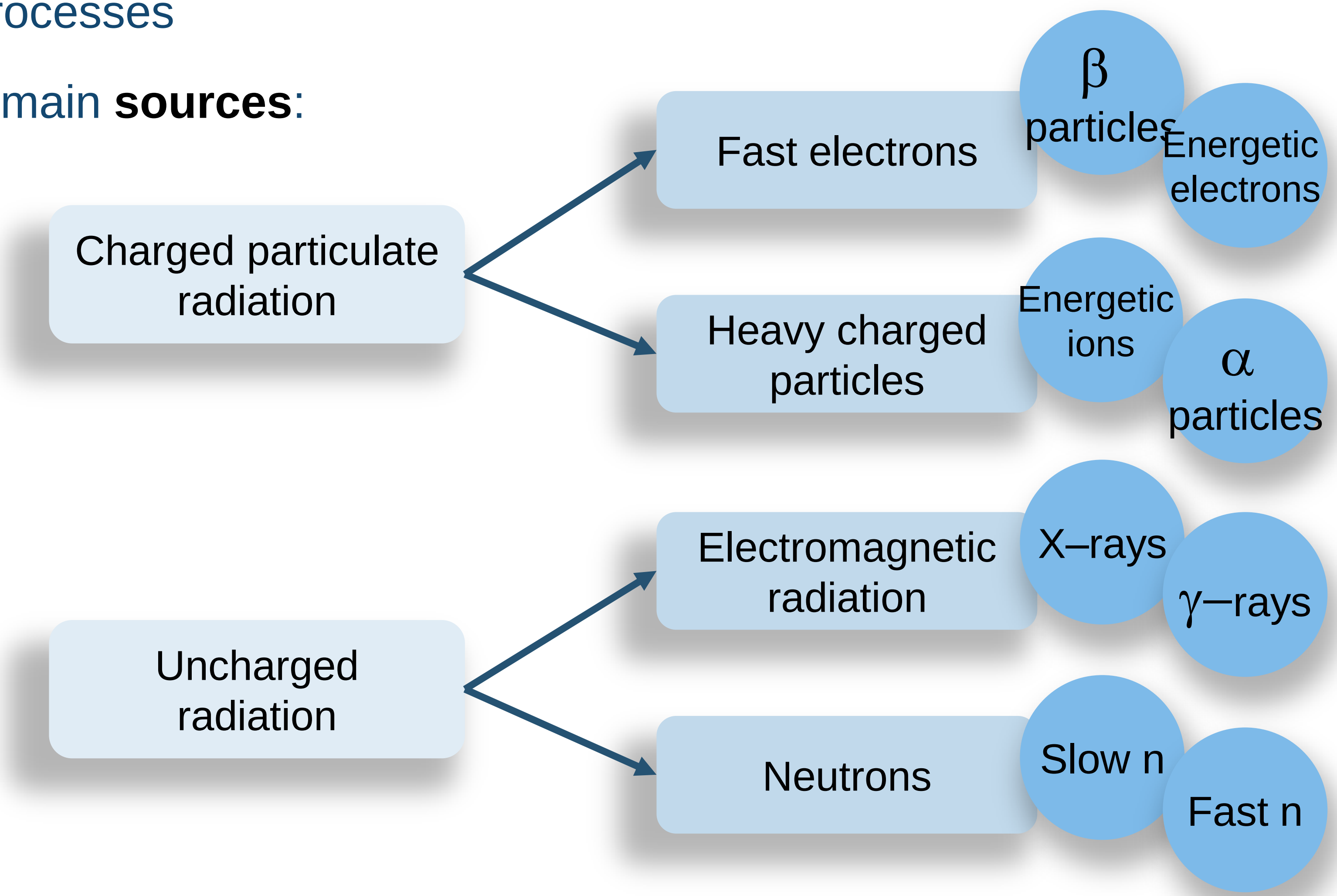
RTDa – Politecnico & INFN Bari

Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes
- 4 main **sources**:



Radiation sources

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- 4 main **sources**:

Energy range of interest

10 eV ⟷ 20 MeV

E_{min} required to produce ionization in typical materials

β particles | Energetic electrons

Energetic ions | α particles

X–rays | γ–rays

Slow n | Fast n

Ionizing radiations have $E > E_{min}$

Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes

- Sources:

  1. Radioisotope decay by beta-minus emission ("Beta decay")

$$^{A}_{Z}X \rightarrow {}^{\;\;A}_{Z+1}Y + \beta^{-} + \bar{\nu}$$

Fast electrons

β particles

Energetic electrons

Pure beta emitters

Nuclide	Half-Life	Endpoint Energy (MeV)
^{3}H	12.26 y	0.0186
^{14}C	5730 y	0.156
^{32}P	14.28 d	1.710
^{33}P	24.4 d	0.248
^{35}S	87.9 d	0.167
^{36}Cl	3.08×10^{5} y	0.714
^{45}Ca	165 d	0.252
^{63}Ni	92 y	0.067
$^{90}Sr/^{90}Y$	27.7 y/64 h	0.546/2.27
^{99}Tc	2.12×10^{5} y	0.292
^{147}Pm	2.62 y	0.224

Lederer & Shirley 1978

Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes

- Sources:
  1. Beta decay
  2. Internal conversion

$$E_{e^-} = E_{ex} - E_b$$

Fast electrons

β particles

Energetic electrons

Common Conversion Electron Sources

Parent Nuclide	Parent Half-Life	Decay Mode	Decay Product	Transition Energy of Decay Product (keV)	Conversion Electron Energy (keV)
^{109}Cd	453 d	EC	^{109m}Ag	88	62 84
^{113}Sn	115 d	EC	^{113m}In	393	365 389
^{137}Cs	30.2 y	β^-	^{137m}Ba	662	624 656
^{139}Ce	137 d	EC	^{139m}La	166	126 159
^{207}Bi	38 y	EC	^{207m}Pb	570 1064	482 554 976 1048

Lederer & Shirley 1978

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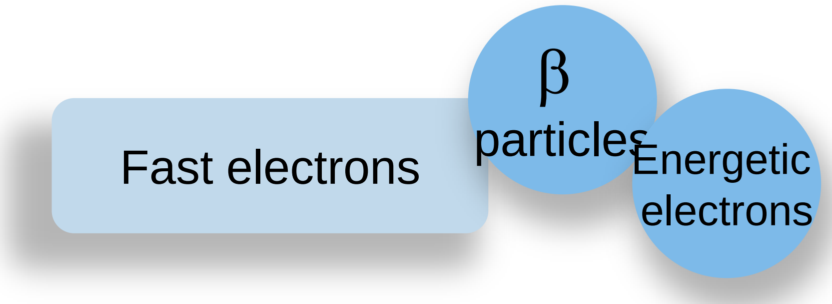


- Sources:
  1. Beta decay
  2. Internal conversion
  3. Auger electrons
  Analogue of internal conversion electrons when the excitation energy originates in the atom rather than in the nucleus. Outer electrons ejected from the atom (discrete energy spectrum).

Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes

- Sources:

  1. Alpha decay

$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha $$

Heavy charged particles

Energetic ions

α particles

Alpha emitting Radioisotpe sources

Source	Half-Life	Alpha Particle Kinetic Energy (with Uncertainty) in MeV		Percent Branching
^{148}Gd	93 y	3.182787	±0.000024	100
^{232}Th	1.4×10^{10} y	4.012	±0.005	77
		3.953	±0.008	23
^{238}U	4.5×10^{9} y	4.196	±0.004	77
		4.149	±0.005	23
^{235}U	7.1×10^{8} y	4.598	±0.002	4.6
		4.401	±0.002	56
		4.374	±0.002	6
		4.365	±0.002	12
		4.219	±0.002	6
^{236}U	2.4×10^{7} y	4.494	±0.003	74
		4.445	±0.005	26
^{230}Th	7.7×10^{4} y	4.6875	±0.0015	76.3
		4.6210	±0.0015	23.4
^{234}U	2.5×10^{5} y	4.7739	±0.0009	72
		4.7220	±0.0009	28
^{231}Pa	3.2×10^{4} y	5.0590	±0.0008	11
		5.0297	±0.0008	20
		5.0141	±0.0008	25.4
		4.9517	±0.0008	22.8
^{239}Pu	2.4×10^{4} y	5.1554	±0.0007	73.3
		5.1429	±0.0008	15.1
		5.1046	±0.0008	11.5

Source	Half-Life	Alpha Particle Kinetic Energy (with Uncertainty) in MeV		Percent Branching
^{240}Pu	6.5×10^{3} y	5.16830	±0.00015	76
		5.12382	±0.00023	24
^{243}Am	7.4×10^{3} y	5.2754	±0.0010	87.4
		5.2335	±0.0010	11
^{210}Po	138 d	5.30451	±0.00007	99+
^{241}Am	433 y	5.48574	±0.00012	85.2
		5.44298	±0.00013	12.8
^{238}Pu	88 y	5.49921	±0.00020	71.1
		5.4565	±0.0004	28.7
^{244}Cm	18 y	5.80496	±0.00005	76.4
		5.762835	±0.000030	23.6
^{243}Cm	30 y	6.067	±0.003	1.5
		5.992	±0.002	5.7
		5.7847	±0.0009	73.2
		5.7415	±0.0009	11.5
^{242}Cm	163 d	6.11292	±0.00008	74
		6.06963	±0.00012	26
^{254m}Es	276 d	6.4288	±0.0015	93
^{253}Es	20.5 d	6.63273	±0.00005	90
		6.5916	±0.0002	6.6

Rytz 1973

Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes

- Sources:

Heavy charged particles

Energetic ions

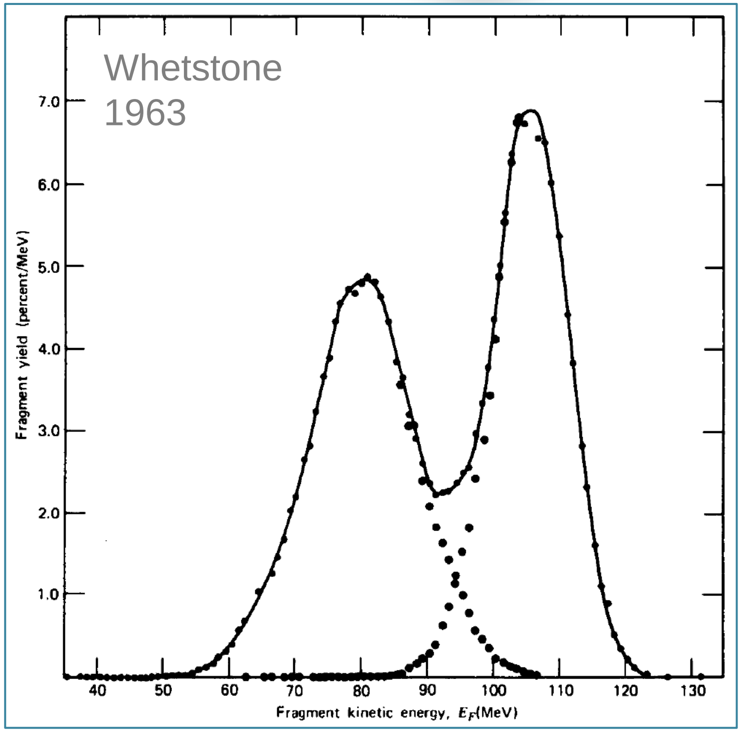
α particles

1. Alpha decay
2. Spontaneous fission

Fission process is the only spontaneous source of energetic heavy charged particles with **mass greater than that of the alpha particle**.

Two **fission fragments** (positive ions) are produced ("light group" and "heavy group")

The distribution in kinetic energy of the ^{252}Cf spontaneous fission fragments



Radiation sources

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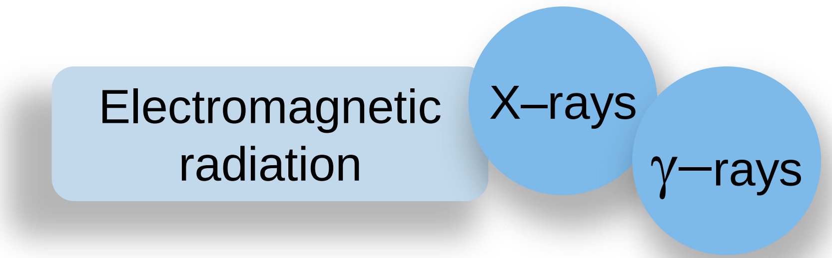
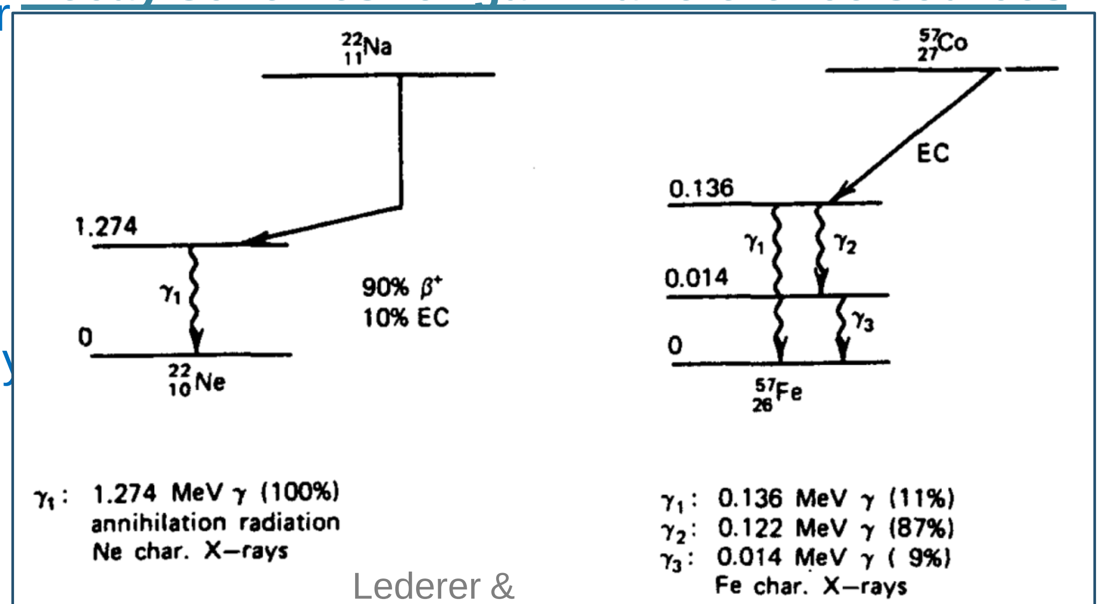


- Sources:
    1. Gamma-rays following beta decay
        - From excited nuclei in their transition to lower-lying nuclear levels
        - Limited to energies below ~2.8 MeV
        - Very specific photon energy, almost monoenergetic

Decay schemes for gamma reference sources



Lederer & Shirley 1978

Radiation sources

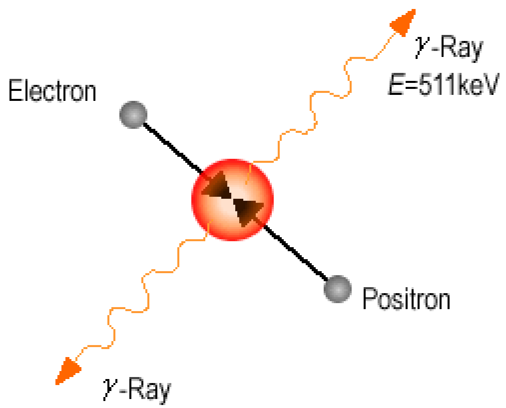
- We are interested in radiation that **originates** in **atomic** or **nuclear** processes

Electromagnetic radiation | X–rays | γ–rays

- Sources:

  1. Gamma-rays following beta decay
  2. Annihilation radiation

  - β+ decay positron and normal electron disappear and are replaced by two oppositely directed 0.511 MeV photons



Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes

- Sources:

  1. Gamma-rays following beta decay
  2. Annihilation radiation
  3. Gamma rays following nuclear reactions

  - ${}^{4}_{2}\alpha + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C^{*} + {}^{1}_{0}n$ ➔ 4.4 MeV photon
  - ${}^{4}_{2}\alpha + {}^{13}_{6}C \rightarrow {}^{16}_{8}O^{*} + {}^{1}_{0}n$ ➔ 6.1 MeV photon

Electromagnetic radiation

X–rays

γ–rays

Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes

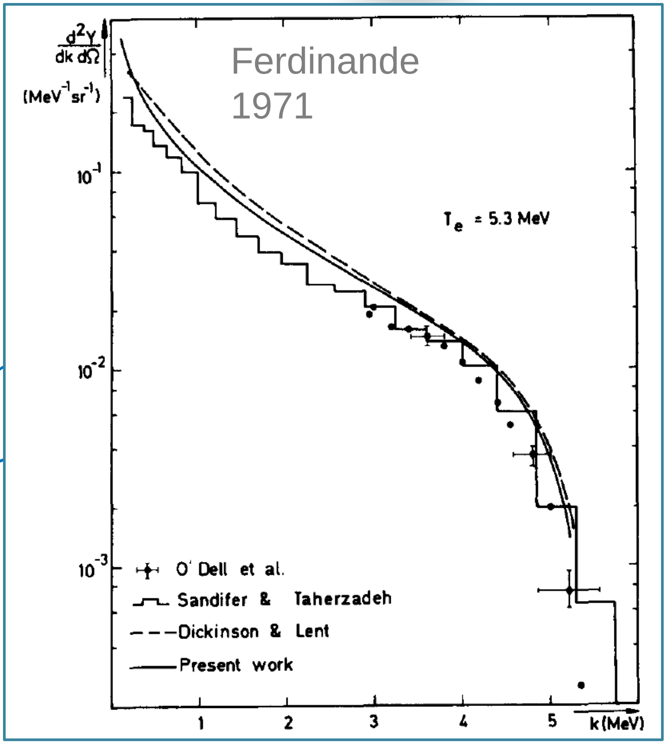
Electromagnetic radiation

X–rays

γ–rays

- Sources:
  1. Gamma-rays following beta decay
  2. Annihilation radiation
  3. Gamma rays following nuclear reactions
  4. Bremsstrahlung

  - Monoenergetic electrons slow down and stop i given material → Bremsstrahlung energy spectru is a continuum with photon energies that extend as high as the electron energy itself



Energy spectrum emitted by 5.3 MeV electrons incident on a Au-W target

Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes

Electromagnetic radiation

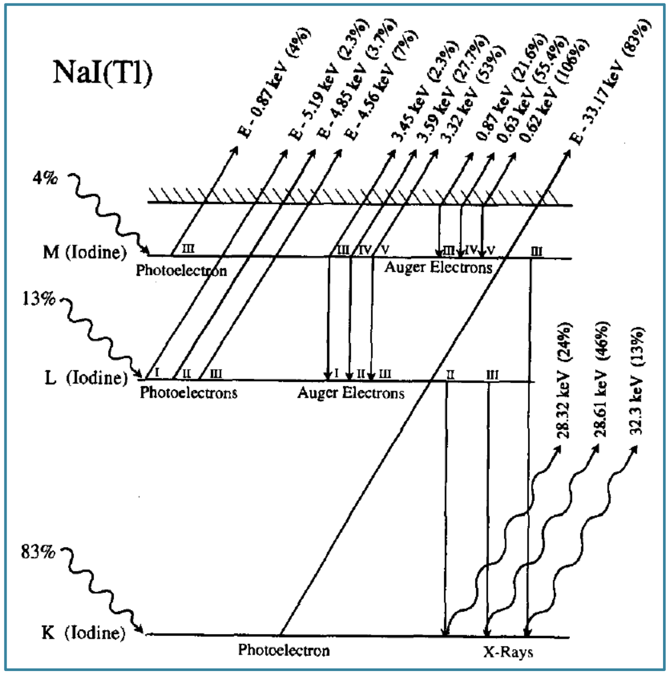
X–rays

γ–rays

- Sources:

  1. Gamma-rays following beta decay
  2. Annihilation radiation
  3. Gamma rays following nuclear reactions
  4. Bremsstrahlung
  5. Characteristic X–rays

  - Disrupted atom rearrangement to its lowest energy or ground state
  - K–shell energy transitions



Radiation sources

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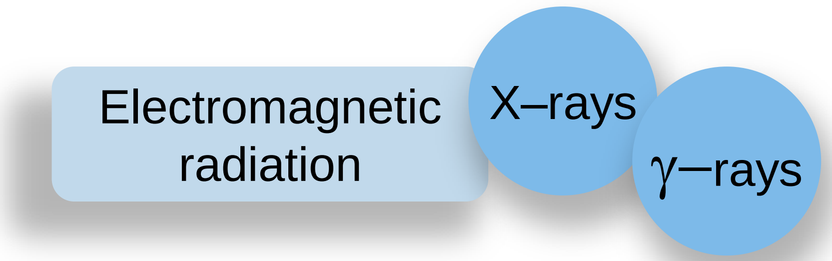


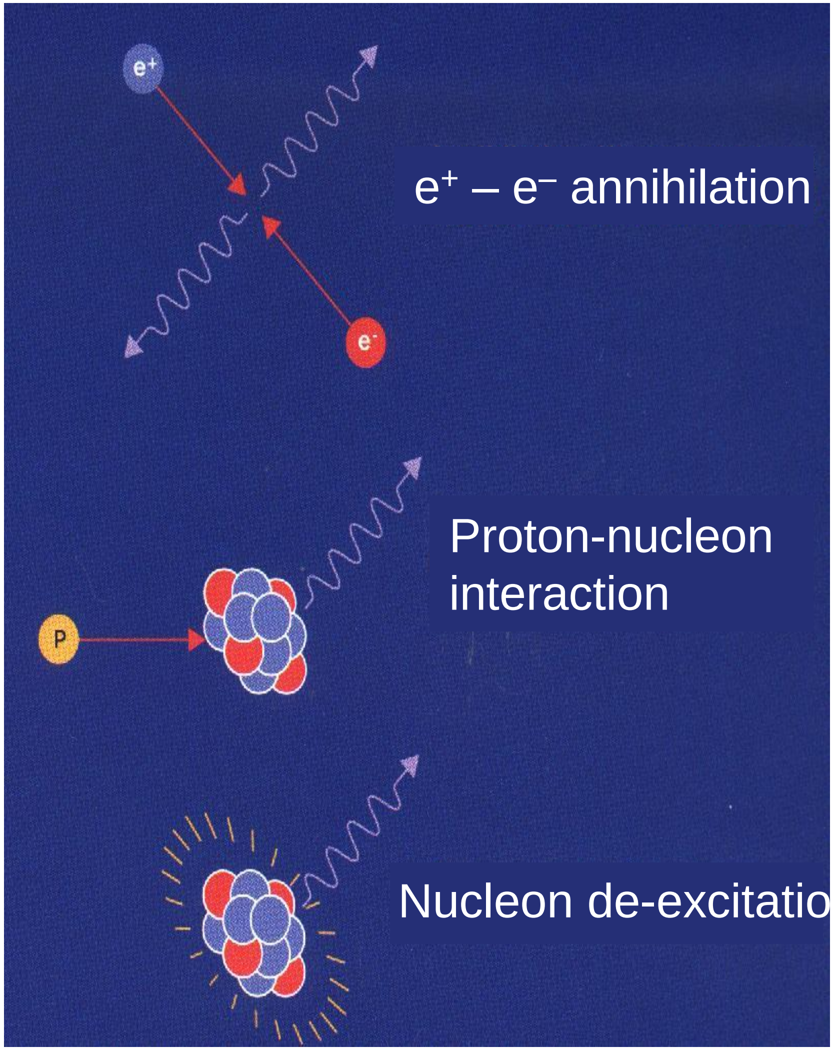
- Sources:

  1. Gamma-rays following beta decay
  2. Annihilation radiation
  3. Gamma rays following nuclear reactions
  4. Bremsstrahlung
  5. Characteristic X–rays
  6. Synchrotron Radiation

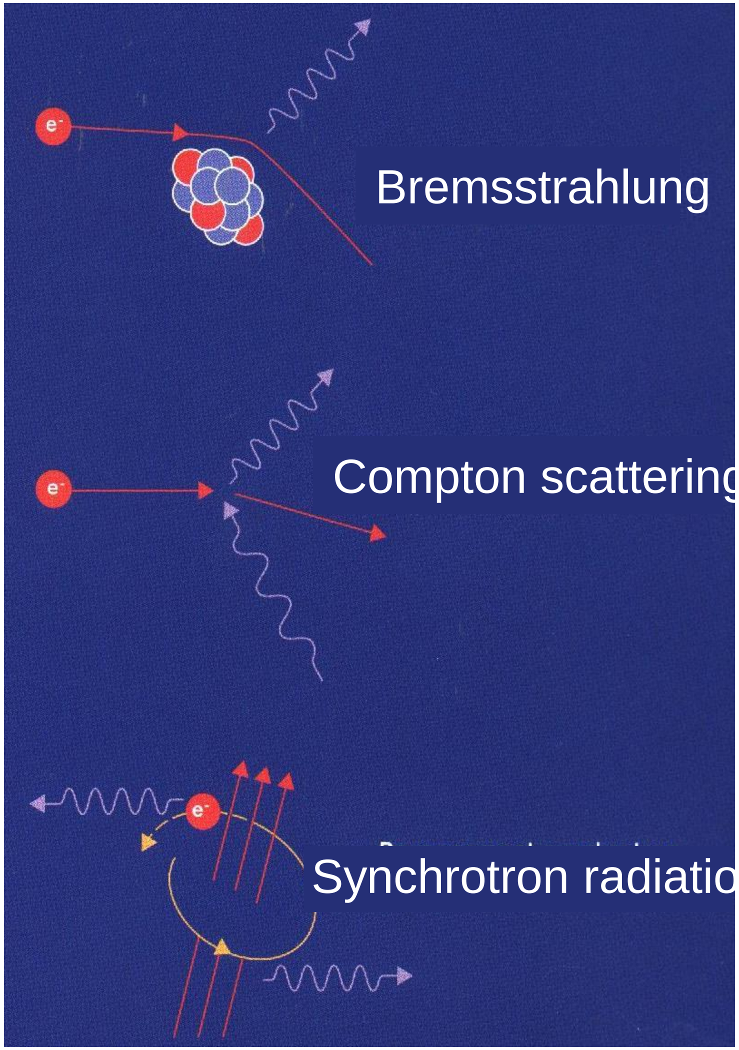
  - Beam of energetic electrons bent into a circular orbit → beam energy radiated away in a tangential direction during each cycle
  - Photon energy can span from a few eV through X-ray energies

Radiation sources

Line emission

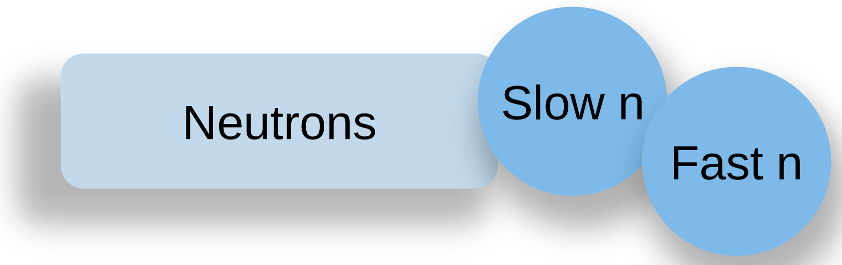


Continuum emission



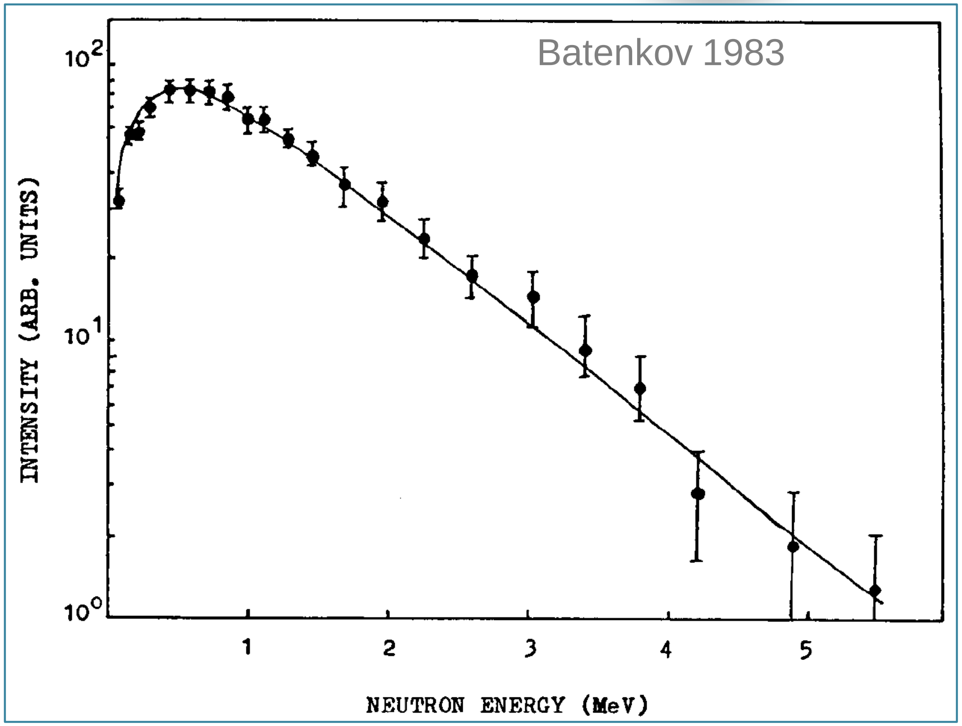
Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes



- Sources:
  1. Spontaneous fission

Measured neutron energy spectrum from the spontaneous fission of ^{252}Cf



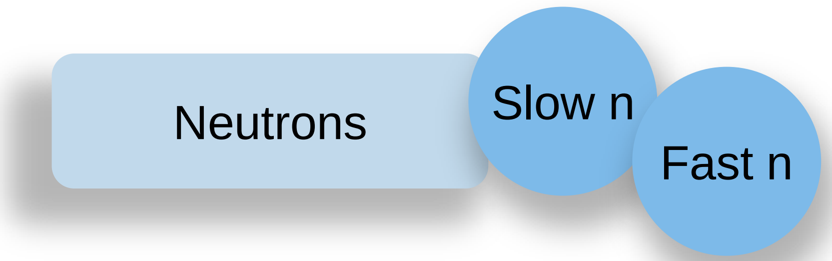
Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes

- Sources:

  1. Spontaneous fission
  2. Radioisotope (α,n) Sources

  - $^{4}_{2}\alpha + ^{9}_{4}Be \rightarrow ^{12}_{6}C + ^{1}_{0}n$



Characteristics of Be(α, n) Neutron Sources

Source	Half-Life	E_α (MeV)	Neutron Yield per 10^6 Primary Alpha Particles		Percent Yield with $E_n < 1.5$ MeV	
			Calculated	Experimental	Calculated	Experimental
^{239}Pu/Be	24000 y	5.14	65	57	11	9–33
^{210}Po/Be	138 d	5.30	73	69	13	12
^{238}Pu/Be	87.4 y	5.48	79[a]	—	—	—
^{241}Am/Be	433 y	5.48	82	70	14	15–23
^{244}Cm/Be	18 y	5.79	100[b]	—	18	29
^{242}Cm/Be	162 d	6.10	118	106	22	26
^{226}Ra/Be + daughters	1602 y	Multiple	502	—	26	33–38
^{227}Ac/Be +daughters	21.6 y	Multiple	702	—	28	38

Geiger & Van der Zwan 1975

Radiation sources

- We are interested in radiation that **originates** in **atomic** or **nuclear** processes

Neutrons

Slow n

Fast n

- Sources:

   1. Spontaneous fission
   2. Radioisotope (α,n) Sources
   3. Photoneutron sources

- ${}^{9}_{4}Be + h\nu \rightarrow {}_{46}^{8}Be + {}^{1}_{0}n$ → -1.666 MeV
- ${}^{2}_{1}H + h\nu \rightarrow {}^{1}_{1}H + {}^{1}_{0}n$ → -2.226 MeV

Gamma-ray photons with energy of at least the negative of the Q-value is required to make the reactions energetically possible, so that only relatively high-energy gamma rays can be applied

Radiation sources

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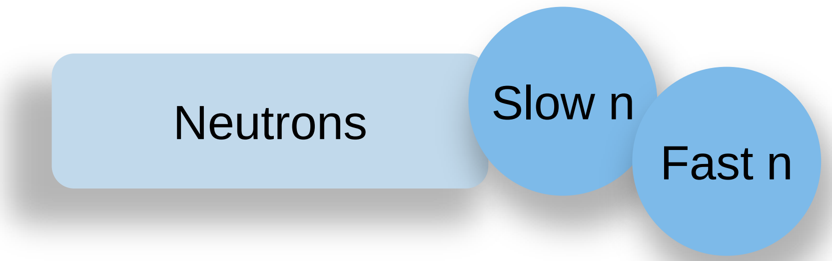


- Sources:
  1. Spontaneous fission
  2. Radioisotope (α,n) Sources
  3. Photoneutron sources
  4. Reactions from accelerated charged paritcles

  - ${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n$ (D-D reaction)
  - ${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$ (D-T reaction)

Radiation interactions

- Need to understand **how** the **radiation** to be detected **interacts with and loses its energy** in the **material** of the detector itself

Charged particulate radiation	Uncharged radiation
Heavy charged particles	Neutrons
Fast electrons	Electromagnetic radiation

Radiation interactions

- Need to understand **how** the **radiation** to be detected **interacts with and loses its energy** in the **material** of the detector itself.

Charged particulate radiation	Uncharged radiation
Heavy charged particles	Neutrons
Fast electrons	Electromagnetic radiation

Continuously interact through the **Coulomb force** with the **electrons** present in any medium through which they pass

Radiation interactions

- Need to understand **how** the **radiation** to be detected **interacts with and loses its energy** in the **material** of the detector itself.

Charged particulate radiation	Uncharged radiation
Heavy charged particles	Neutrons
Fast electrons	Electromagnetic radiation

Not subject to the coulomb force. Must first undergo a **"catastrophic" interaction** that **radically alters** the properties of the incident radiation in a single encounter

Radiation interactions

- Need to understand **how** the **radiation** to be detected **interacts with and loses its energy** in the **material** of the detector itself.

Charged particulate radiation

Uncharged radiation

10^{-5} m

Heavy charged particles

Neutrons

10^{-1} m

distance of penetratio n **10^{-3} m**

Fast electrons

Electromagnetic radiation

average mean free path **10^{-1} m**

E.g. Devices designed to detect **gamma rays** are designed to fully **stop the secondary electrons** so that their entire energy may contribute to the **output signal**

Results of such catastrophic Interactions

Interaction of charged particles

- Nature of the interaction
  - Primarily: Coulomb forces between **positive charge of particles** (e.g. alpha particles) and the **negative charge of the orbital electrons** within the absorber atoms
  - Charged particle interacts simultaneously with many electrons
    - In any one such encounter, the electron feels an **impulse** from the attractive Coulomb force as the particle passes its vicinity

EXCITATION
Electron of the absorber atom gets raised to a higher-lying shell

IONIZATION
Electron of the absober atom is completely removed

→ Energy transfer
→ Velocity decrease

Interaction of charged particles

- Charged particles characterized by a **definite range** in a given absorber material
  - Range = distance beyond which no particles will penetrate
  - Stopping power: $S = -\frac{dE}{dx}$ → dE differential energy loss, dx differential path length
  - *Bethe formula*

$$-\frac{dE}{dx} = \frac{4\,\pi\, e^4 z^2}{m_e\, v^2} \cdot NZ \left[ln\left(\frac{2m_e v^2}{I\,(1-\beta^2)}\right) - \beta^2 \right]$$

Charged particle

v speed
ze charge
E energy

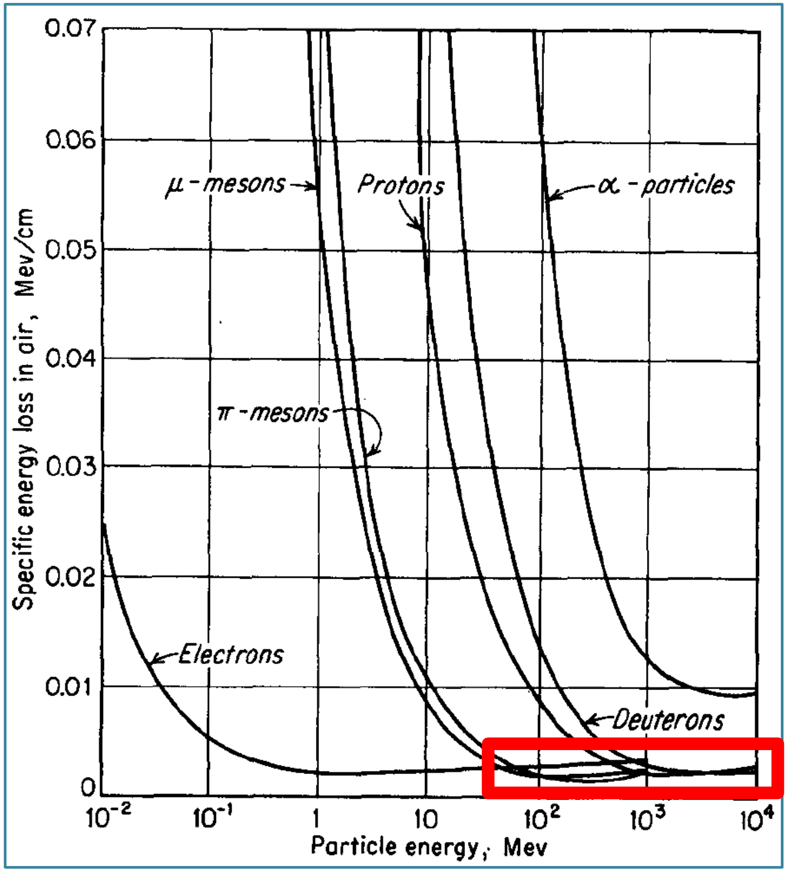
Target material

I mean excitation potential
Z atomic number
N number density

$\beta = v/c$

Interaction of charged particles

Variation of the specific energy loss in air versus energy of charged

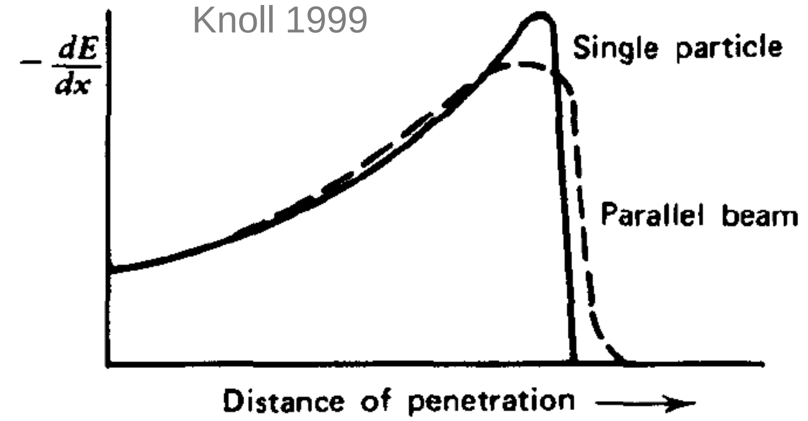


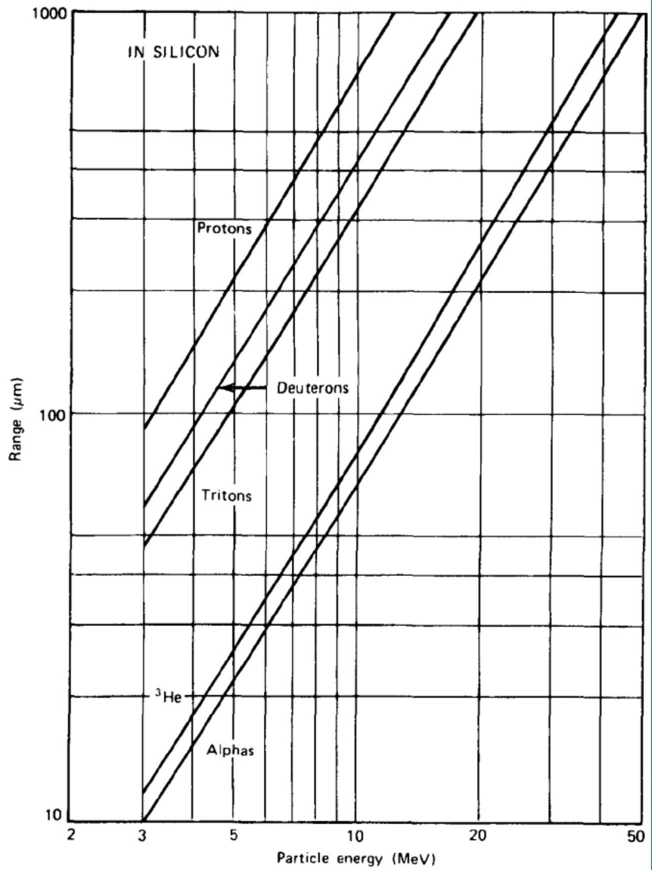
Beiser 1952

- Particles with the **greatest charge** will have the **largest specific energy loss**
- dE/dx approaches a **near-constant broad minimum value** at energies **above several hundred MeV**, where their velocity approaches the **velocity of light**
  - Relativistic particles with similar energy loss behavoior: "minimum ionizing particles" (~2 MeV per g/cm^2)

Interaction of charged particles

Specific energy loss along the track of an alpha particle of several MeV initial energy: BRAGG CURVE





Skyrme 1967

Range-energy curves calculated for different charged particles in silicon.

The **near-linear behavior** of the log-log plot over the energy range shown suggests an **empirical relation** to the form $R = aE^b$, where the slope-related parameter b is not greatly different for the various particles

Interaction of electrons

- Energy loss rate **lower than for heavy charged particles**
  - Electrons follow a **much more tortuous path** through absorbing materials
  - **Much larger fraction of electron energy** can be lost in a single encounter
    - Also: energy may be lost by **radiative processes** as well as by **coulomb interactions**
  - Modification to the Bethe formula
  - The total linear stopping power for electrons is the sum of the **collisional and radiative losses**
  - Electron **path length** in typical absorbers **is hundreds of times greater**
    - 2 mm/MeV (low-density material)

Interaction of gamma rays

3 MAJOR MECHANISMS

1. Photoelectric absorption
2. Compton scattering
3. Pair production

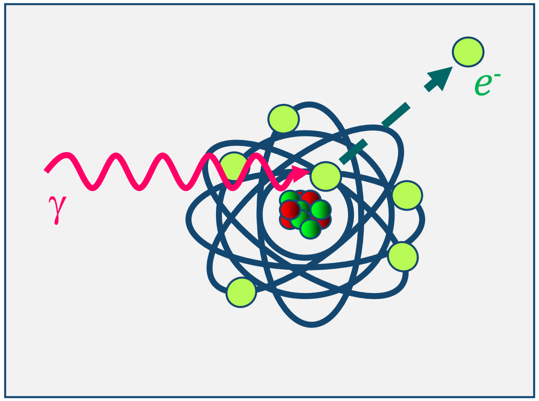
- All these processes:
  - Lead to **partial** or **complete transfer** of the gamma-ray **photon** energy to **electron** energy
  - Produce **sudden** and **abrupt** changes in the gamma-ray photon history
    - Photon **disappears** or is **scattered** through a significant angle

Interaction of gamma rays

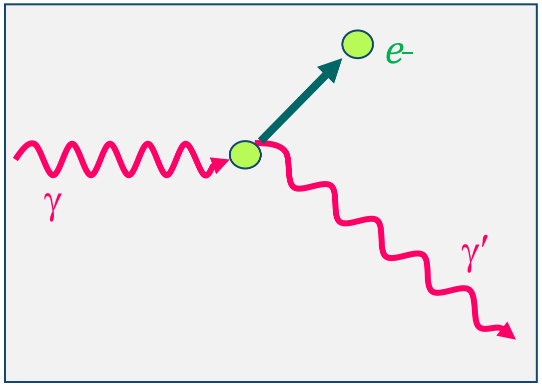
1. **Photoelectric absorption** (low energies)
   - Photon completely disappears
   - Photoelectron is ejected by the atom

     $$E_{e^-} = h\nu - E_b$$

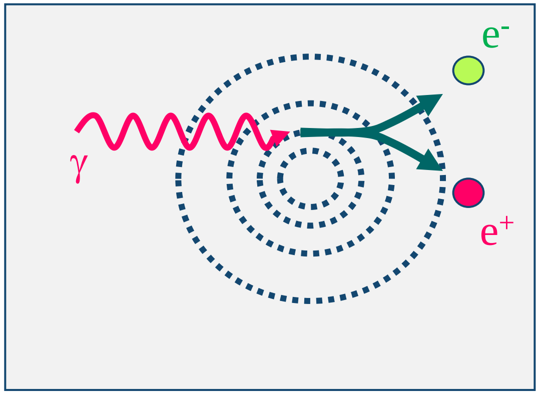
     E_b photoelectron binding energy
   - Characteristic X-ray photons may be generated



2. **Compton scattering (medium energies)**
   - Deflection of incoming photon (angle θ)
     - Angular distribution of scattered photons predicted by the Klein-Nishina formula
   - Scattered photon: $h\nu' = h\nu \,/\, \left(1 + \frac{h\nu}{m_e c^2}(1 - cos\theta)\right)$

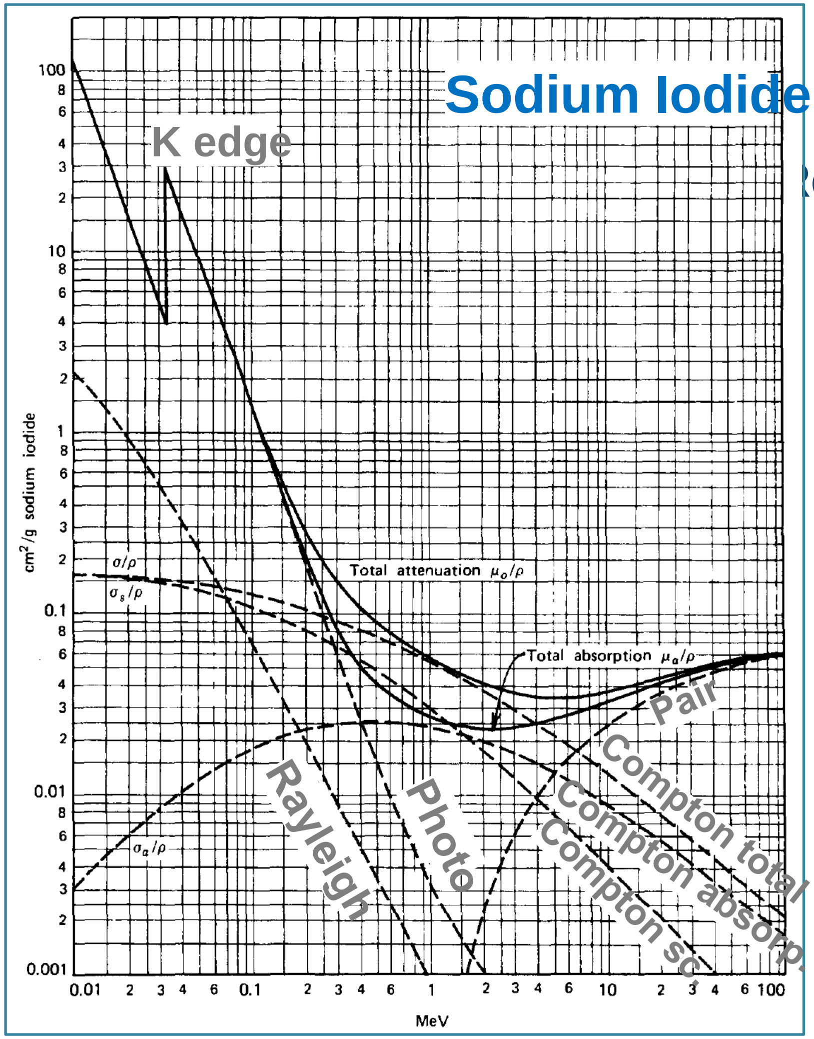


3. **Pair production (E > 1.022 MeV)**
   - Interaction in the Coulomb field of a nucleus
   - Photon disappears
     - Electron-positron pair
     - Positron annihilation produces 2 photons



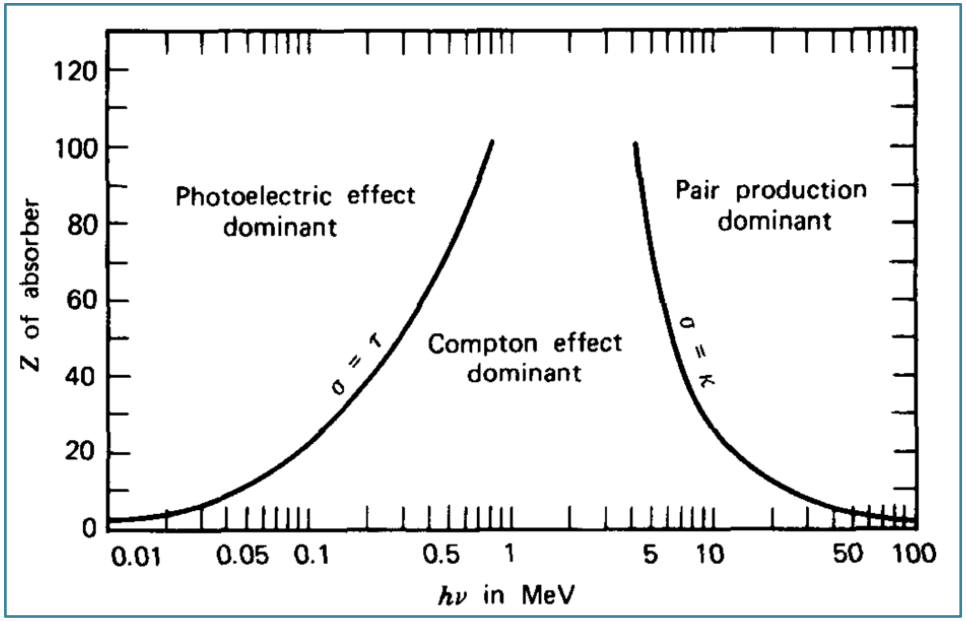
Interaction of gamma rays

Energy dependence of the various gamma-ray interaction processes in NaI



Relative importance of the three major types of gamma-ray interaction

Lines show the values of Z and hν for which two neighboring effects are equally probable



Evans 1955

Interaction of gamma rays

GAMMA-RAY ATTENUATION

- Attenuation coefficients:
  - Linear attenuation coefficient $\mu = \tau_{photo} + \sigma_{Compton} + \kappa_{pair}$
  - Mean free path $\lambda = \frac{1}{\mu}$ (from few mm to tens of cm)
  - Mass attenuation coefficient $= \frac{\mu}{\rho}$ (ρ medium density)
- Attenuation law: $\mathrm{I} / \mathrm{I}_0 = \mathrm{e}^{-(\mu/\rho)\rho t}$
  - Absorber mass thickness $= \rho t$
- Buildup factor
  - Simple multiplicative correction $\mathrm{I} / \mathrm{I}_0 = \mathrm{B}(t, E_\gamma)\mathrm{e}^{-\mu t}$
  - Takes into account "Broad beam" or "bad geometry" conditions that contribute with additional secondary gamma-rays

    ➔ Depends on the type and specific geometry of the detector

Interaction of neutrons

Slow neutrons

- Elastic scattering with absorber nuclei
  - Very probable
  - Serve to bring the slow neutron into thermal equilibrium with the absorber medium before a different type of interaction takes place

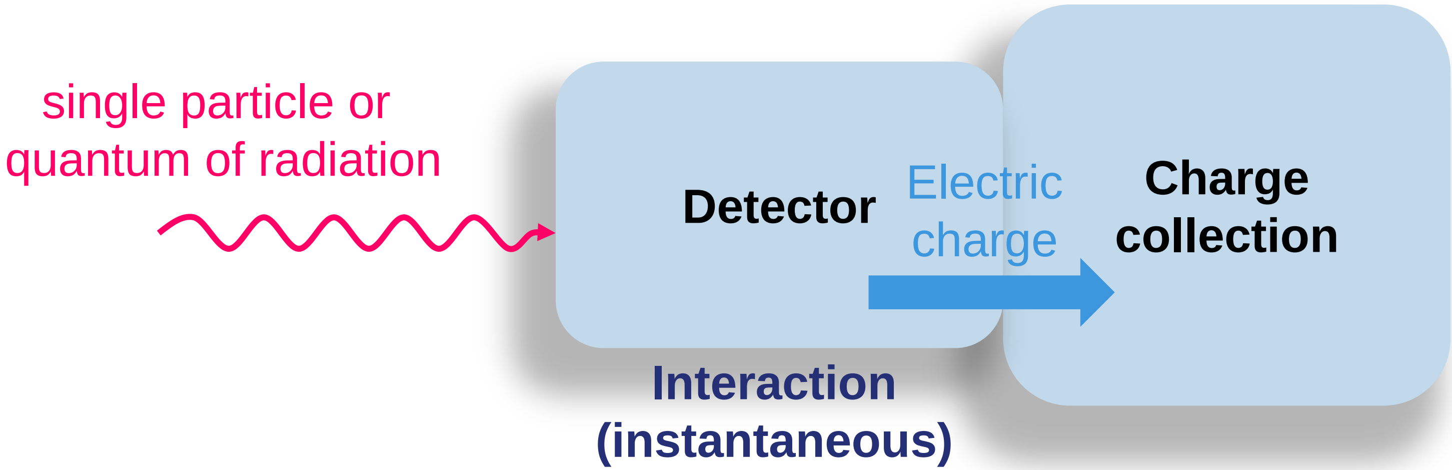
  → Thermal neutrons at room temperature ~0.025 eV.
- Large set of neutron-induced nuclear reactions
  - Radiative capture reaction is most probable

Fast neutrons

- With increasing neutron energy scattering becomes important
  - Secondary radiation: recoil nuclei
  - Neutron loses energy and is moderated by hydrogen to lower energies
- Inelastic scattering at higher energies
  - Emission of secondary gamma rays

General properties of radiation detectors

- Simplified detector model



Charge collection time reflects both the **mobility of the charge carriers** within the detector active volume and the **average distance** that must be traveled before arrival at the collection electrodes

OPERATION MODES

1. Pulse mode
2. Current mode
3. Mean square voltage mode

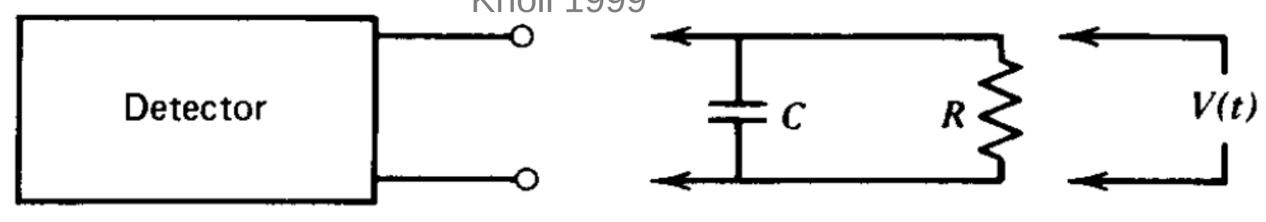
RADIATION SPECTROSCOPY

General properties of radiation detectors

The nature of the signal pulse produced from a single event depends on the input characteristics of the circuit to which the detector is connected

EQUIVALENT CIRCUIT

Knoll 1999



- R input resistance of the circuit (e.g. preamplifier)
- C equivalent capacitance (detector+cables+preamplifier)
- $V(t)$ time-dependent fundamental signal voltage
- $\tau = RC$ time constant of the measuring circuit

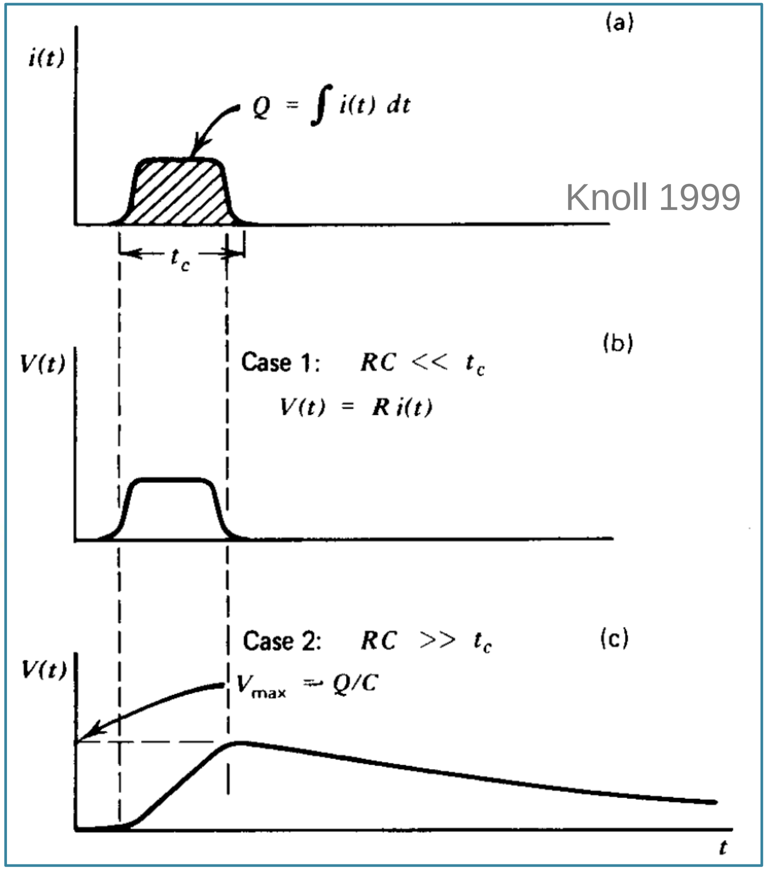
- Operation mode $\tau \gg t_c$: time constant of the external circuit is much larger than the **detector charge collection time** t_c

General properties of radiation detectors

(a) Assumed current output from a detector
(b) Signal Voltage for $\tau \ll t_c$
(c) Signal Voltage for $\tau \gg t_c$

1. The signal **rise time** is determined by the charge collection time **within the detector** itself
2. The signal **decay time** (to restore the signal voltage to zero) is determined by the time constant of the **load circuit**
3. The amplitude of the signal pulse is directly proportional to the corresponding charge generated within the detector

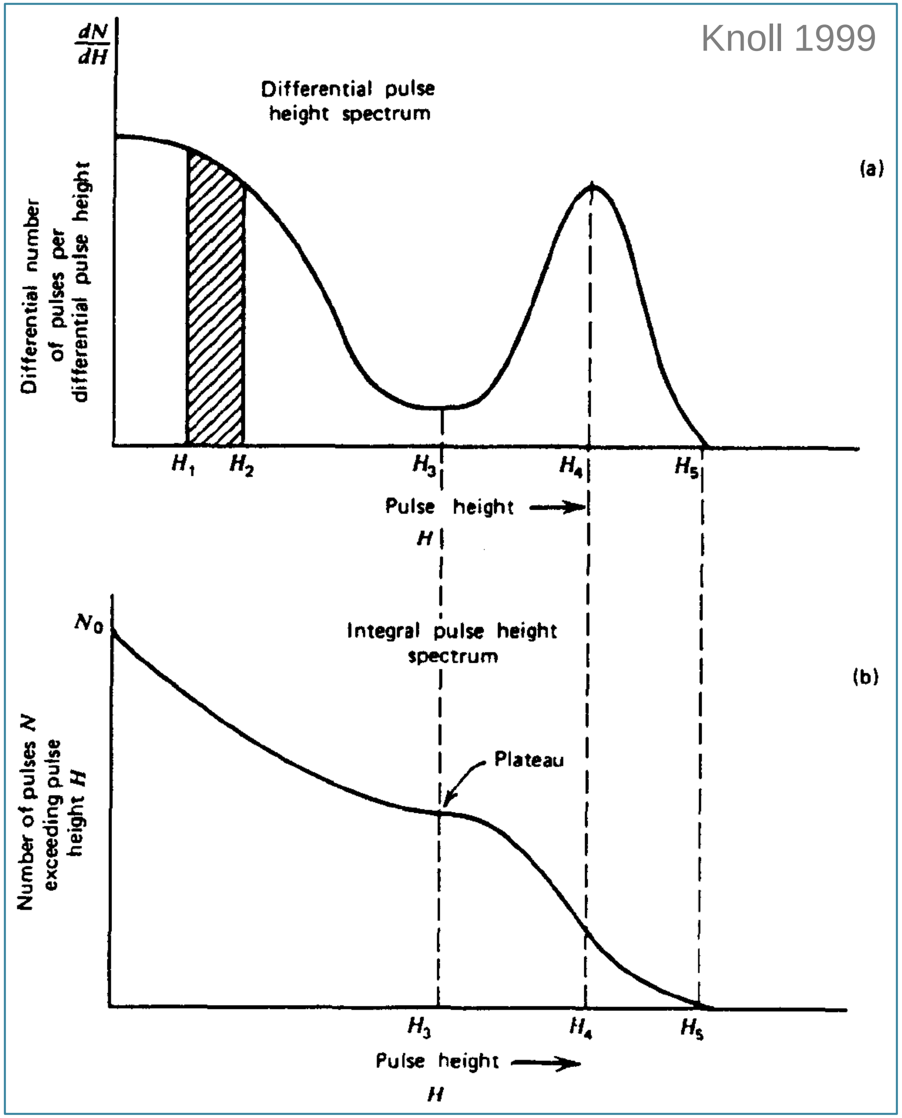
$$V_{max} = \frac{Q}{C}$$



Knoll 1999

Amplitude of each individual pulse **reflects the amount of charge** generated due to each individual **interaction**. Proportionality holds if **C stays constant!**

General properties of radiation detectors



Pulse amplitude distribution

- Fundamental property of the detector output used to deduce information about the incident radiation or the operation of the detector itself

a) Differential pulse height $\frac{dN}{dH}$

b) Integral pulse height N (less common)

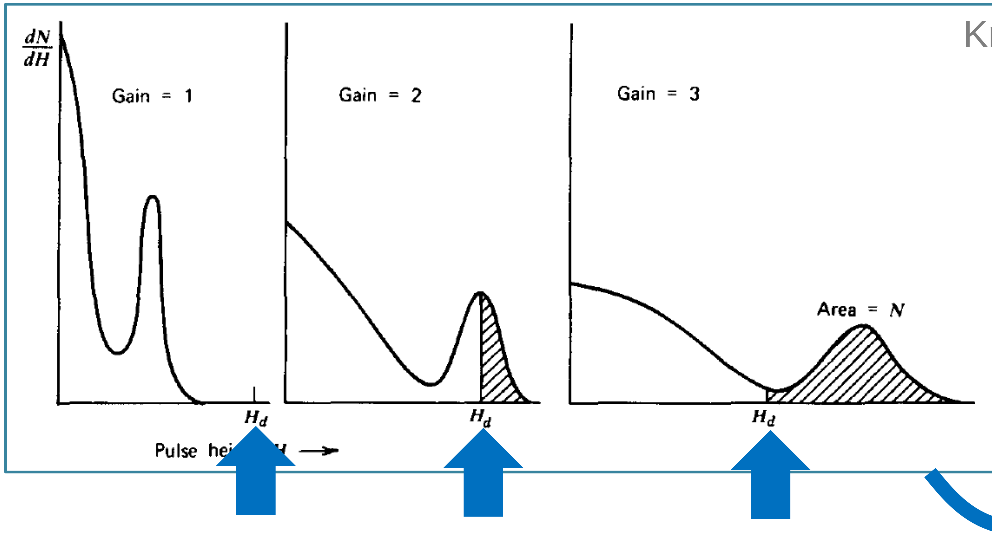
General properties of radiation detectors

- Pulses from the detector are fed to a **counting device** with a fixed discrimination level. Signal pulses must **exceed** a given level H_d in order to be registered by the counting circuit (concept of **THRESHOLD**)
    - H_d **may be varied** during the course of the measurement to provide information about the amplitude distribution of the pulses

- How to chose a stable operating point: **Counting plateau**
    - **Valleys** in the differential distribution / **regions** of minimum slope in the integral distribution
    - Represent areas of operation in which **minimum sensitivity to drifts in discrimination level** are achieved

General properties of radiation detectors

Counting curves generated by varying the gain under constant source



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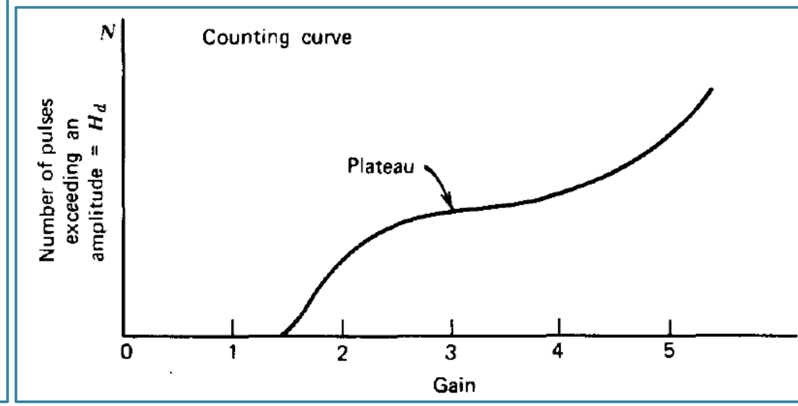


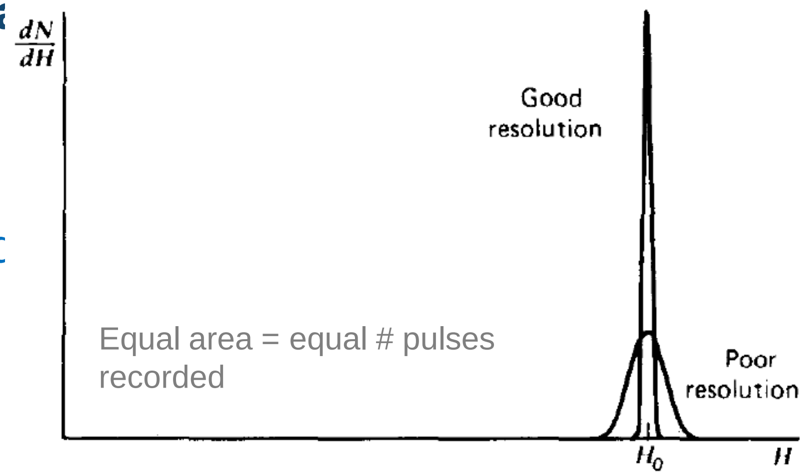
- Three different values of voltage gain applied to the same source of pulses
  - 1: no counts recorded, 2: some counts recorded, 3: more counts recorded
- **Counting curve**
  - Number of pulses recorded **as a function of the gain** applied

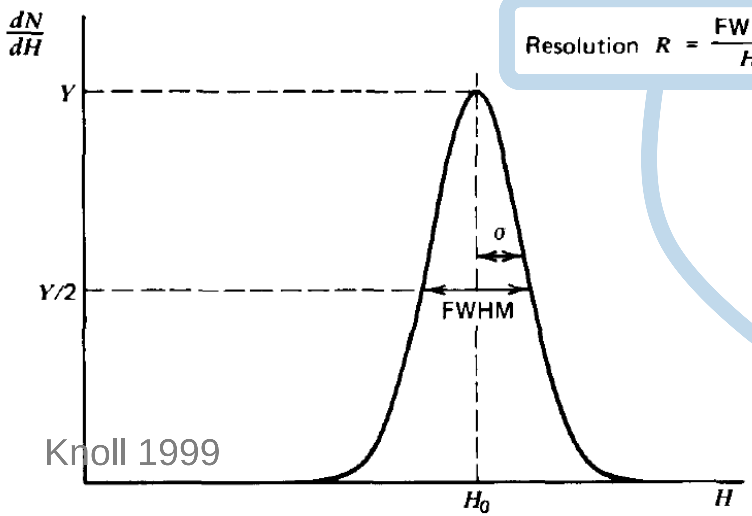
General properties of radiation detectors

Response function to a monoenergetic source of radia

- Areas under each peak are equal
- Width reflects the fact that a large **amount of fluctuation** was recorc from pulse to pulse even though the same energy was deposited in the detector for each event

Knoll 1999





Resolution $R = \frac{FWHM}{H_0}$

Definition of **detector ENERGY RESOLUTION**

- For peaks whose shape is **Gaussian** with standard deviation σ: **FWHM = 2.35 σ**.

Semiconductor diode detectors 1 %
Scintillation detectors 5–10 %

General properties of radiation detectors

ENERGY RESOLUTION

- Rule of thumb: one should be able to **resolve two energies** that are **separated by more than one** value of the detector FWHM
- Sources of **imperfect** energy resolution:

$$FWHM^2_{overall} = FWHM^2_{statistical} + FWHM^2_{noise} + FWHM^2_{drift} + \cdots$$

1. **Statistical noise** arising from the discrete nature of the measured signal
   - IRREDUCIBLE minimum amount of fluctuation
   - Often DOMINANT source of fluctuation
   - Arises from the fact that the charge generated within the detector by a quantum of radiation is not a continuous variable but instead represents a **discrete number of charge carriers** which is subject to **random fluctuation**
2. **Random noise** within the detector and instrumentation system
3. **Drifts** of the operating characteristics of the detector

General properties of radiation detectors

- Formation of each charge carrier = Poisson process
  - Total number of charge carriers generated = $\boldsymbol{N}$
  - Standard deviation = $\sqrt{\boldsymbol{N}}$
- If this were the only source of fluctuation in the signal, the **response function** should have a **Gaussian shape**, because N is typically a large number:

$$G(H) = \frac{A}{\sigma\sqrt{2\,\pi}}\, exp\left(-\frac{(H - H_0)^2}{2\sigma^2}\right)$$

  - Width $\sigma = FWHM/2.35$, Centroid H_0 and Area A
- If the detector's response is **LINEAR**, then $H_0 = KN$ and $\sigma = K\sqrt{N}$:
  - Limiting resolution $R|_{Poisson\ limit} \equiv \frac{FWHM}{H_0} = \frac{2.35\,K\sqrt{N}}{KN} = \frac{2.35}{\sqrt{N}}$
  - **Ideal detector** hould have **as many charge carriers** generated per event as possible!
    - **N~55000 → R~1%**

R improves (decreases) if N is large

General properties of radiation detectors

- **Processes** that give rise to the formation of each individual charge carrier are **not independent**
  - ➔ The total number of charge carriers **cannot** be described by simple Poisson statistics
  - ➔ **Fano factor**
    - Attempt to quantify the departure of the observed statistical fluctuations in the number of charge carriers from pure Poisson statistics

$$F \equiv \frac{\text{observed variance in } N}{\text{Poisson predicted variance } (= N)}$$

- Hence

$$R\Big|_{\text{Statistical limit}} \equiv \frac{2.35\,\sqrt{N}\sqrt{F}}{KN} = 2.35\,\sqrt{\frac{F}{N}}$$

F <1 for semiconductor or diode detectors
F~1 for scintillator detectors

General properties of radiation detectors

DETECTION EFFICIENCY

1. **Absolute efficiency**

$$\epsilon_{abs} = \frac{\textit{number of pulse recored}}{\textit{number of radiation quanta emitted by the source}}$$

- Depends on **detector properties** + details of the **counting geometry**

2. **Intrinsic efficiency**

$$\epsilon_{int} = \frac{\textit{number of pulse recored}}{\textit{number of radiation quanta incident on detector}}$$

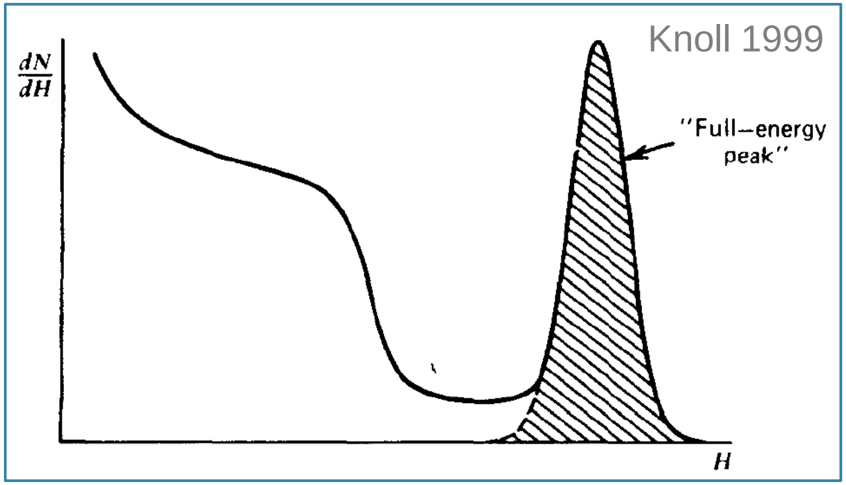
- Depends on detector properties (material, radiation energy, physical thickness of the detector in the direction of the incident radiation)
- Independent of the solid angle Ω subtended by the detector (and the distance from the source to the detector)

$$\epsilon_{int} = \epsilon_{abs} \cdot 4\pi/\Omega$$

General properties of radiation detectors

- **TOTAL EFFICIENCY**

  Sum over the **whole area subtended by the curve,** regardless of amplitude: all interactions (all E) are counted



→BUT: Any measurement system always imposes a requirement that pulses be larger than some finite **threshold level** set to **discriminate** against very small **pulses from electronic noise** sources

- **PEAK EFFICIENCY**

  Sum over those interactions that deposit **the full energy of the incident radiation**

  - Peak that appears at the highest end of the spectrum.

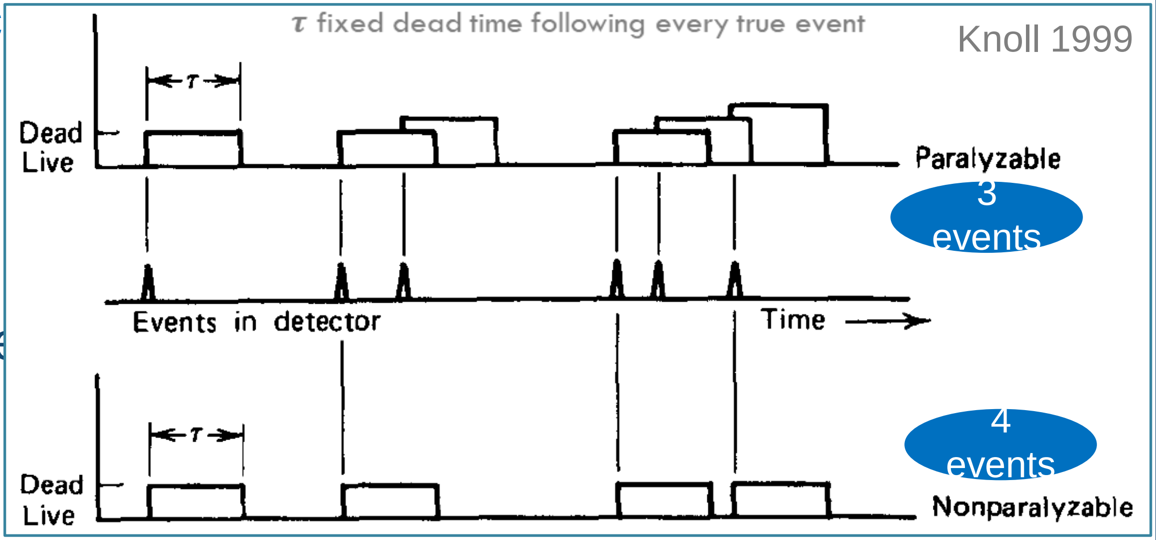
- **PEAK-TO-TOTAL RATIO**

$$r = \frac{\epsilon_{peak}}{\epsilon_{total}}$$

General properties of radiation detectors

DEAD TIME

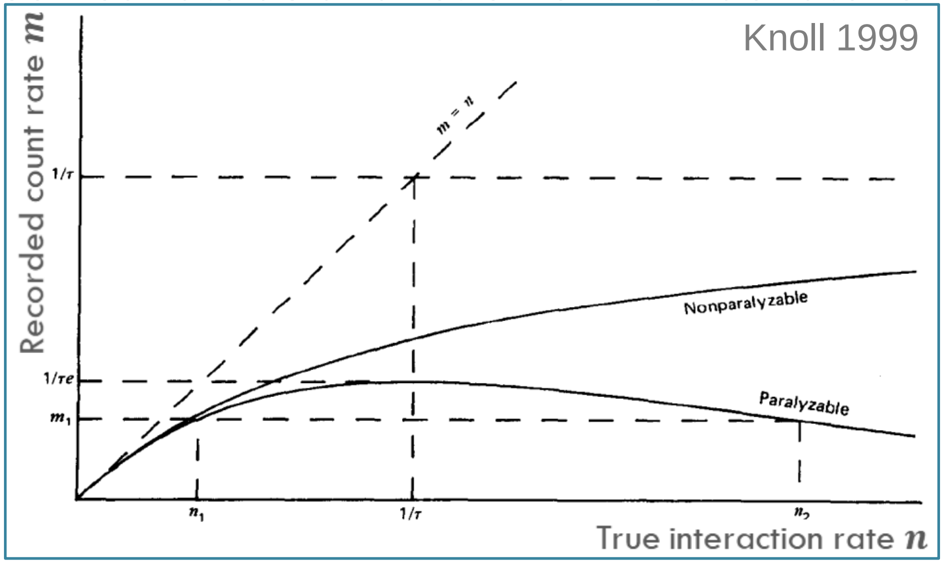
- **Minimum or limiting amount of time** that must **separate two events** in order to be recorded as two separate pulses. Can be determined by
  - Processes in the detector itself
  - Associated electronic



- **Paralyzable** and **nonparalyzable** models predict the same first-orde losses and differ only when true event rates are high
  - Represent **two extremes** of idealized system behavior
  - **Real counting systems** will often display an **intermediate behavior!**

General properties of radiation detectors

Variation of the observed rate as a function of the true rate for two models of dead



$$n = \frac{m}{1 - m\tau}$$

$$m = n e^{-n\tau}$$

- **At low rates: models give similar results**. At high rates:
  - **Nonparalyzable model** approaches **asymptotic value for the observed rate**, representing the situation in which the **counter barely has time to finish one dead period before starting another**.
  - **Paralyzable model**: observed rate goes through a maximum
    - **Mistakes** in the interpretation of nuclear counting data from paralyzable systems have occurred in the past by overlooking the fact that there are always **two possible true interaction rates** corresponding to a given

Scintillation detector principles

Properties of an ideal scintillation material

- Conversion of **kinetic energy** of charged particle into **detectable light** with **high scintillation efficiency**
- Energy conversion schould be **linear**
- Medium should be **transparent to the wavelength of its own emission** for good light collection
- Decay **time** of the induced luminescence should be **short** for **generation of fast signal pulses**
- The material should be of **good optical quality** and subject to manufacture in **large sizes**
- **Index of refraction should be near that of glass (~1.5)** to permit efficient coupling of the scintillation light to a photomultiplier tube or other light sensor

Scintillation detector principles

Organic-based liquids and plastics

- **Reduced** light output
- **Faster yield**
- **Hydrogen** content makes it preferred for **beta spectro-scopy** and **fast neutron** decay

Inorganic alkali halide crystals

- **Best light output and linearity**
- Relatively **slow** in response time
- High Z value of constituents and high density favor choice for **gamma-ray spectroscopy**

Scintillation detector principles

1. **Fluorescence**
   Prompt emission of **visible radiation** from a substance following its **excitation** by some means
2. **Phosphorescence**:
   Emission of **longer wavelength** light than fluorescence, characteristic **time is generally much slower**
3. **Delayed fluorescence**:
   Same emission spectrum as prompt fluorescence, but **much longer emission time** followin

Good scintillator material:

- Maximize **prompt fluorescence**
- **Minimize** the undesirable contributions of phosphorescence and delayed fluorescence

Scintillation detector principles

- **PULSE MODE** operation of scintillators:
  - Light that can contribute to an output pulse is generally **limited** to the **prompt fluorescence** because the **time constants of the measurement circuit** are set **much smaller** than typical phosphorescence and delayed fluorescence decay times
- **CURRENT MODE** operation of scintillators:
  - Under constant illumination will produce a **steady-state signal current** that is **proportional to the total light yield**, and **all the decay components** will contribute in proportion to their absolute intensity

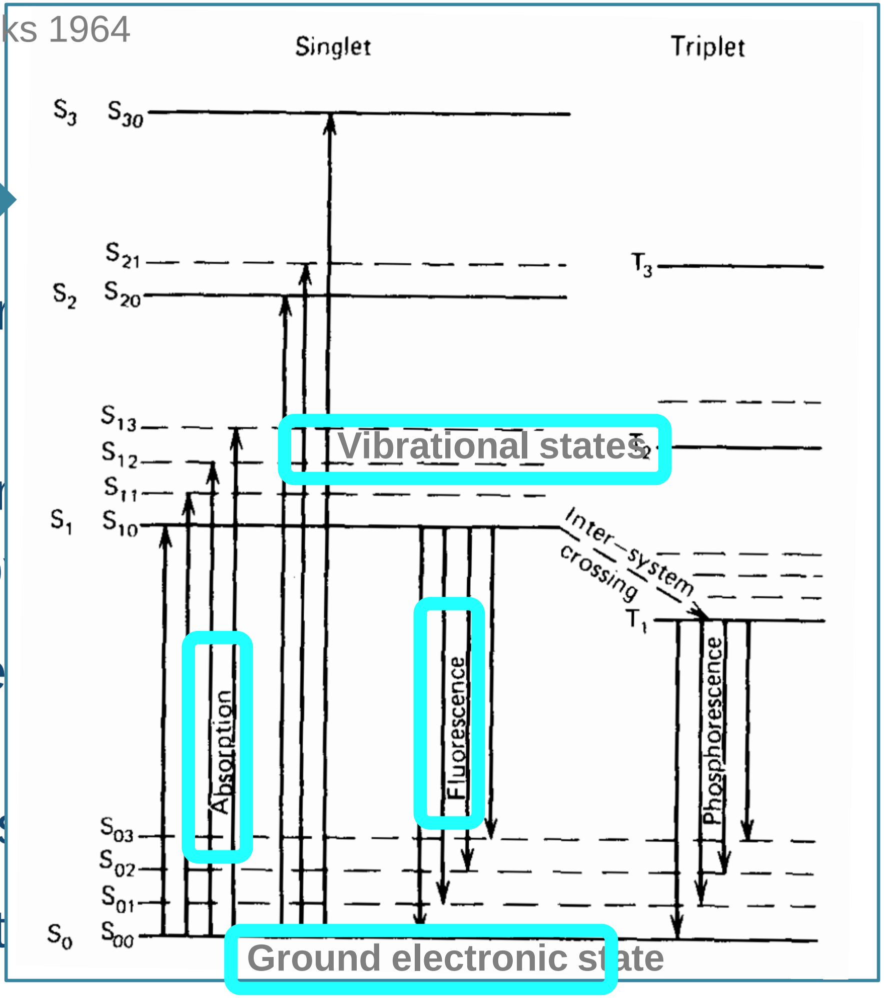
➔ The **light yield** measured from a scintillator operated in **pulse mode** may appear to be **lower than** that deduced from the steady-state **current recorded** from the same scintillator. **BUT**: current mode operation will suffer from memory or **"afterglow" effects** if long-lived

Organic Scintillators

- **Fluorescence**: **transitions** in the energy level structure of single molecule
- Organic molecules with symmetry properties ("π-electron structure")

1. All molecules at room temperatur are in the $\mathbf{S_{00}}$ **state**
2. **Absorption** of kinetic energy fro a charged particle passing nearb
3. Effect of excitation process is the quick production of a population of **excited molecules** in the S_{10} s
4. **Principal scintillation light** emit in transitions to the ground state

Birks 1964



Organic Scintillators

- **Prompt fluorescence intensity**

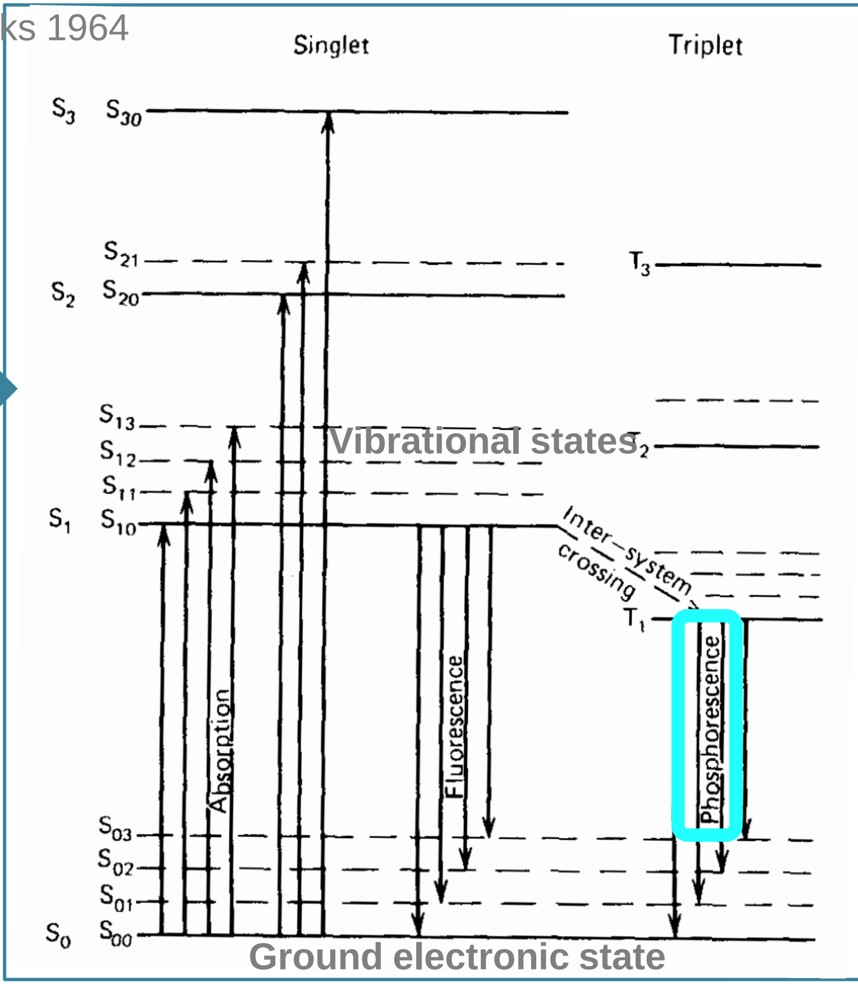
$$I = I_0 e^{-t/\tau}$$

  - τ: prompt fluorescence time
  - t: time following excitation

- Fluorescence decay time for the S_{10} level
  - **Few nanosceconds**

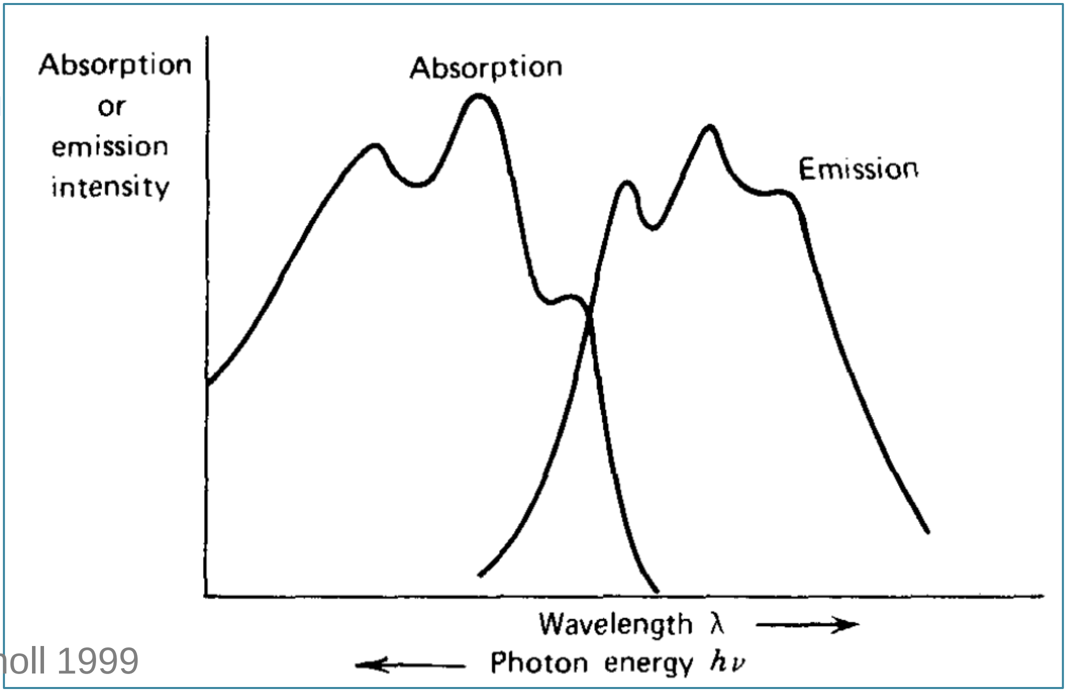
→ Lifetime for triplet state is **much longer** than the singlet one (10^{-3} s)
  - **Phosphorenscence** spectrum

Birks 1964



Organic Scintillators

- Organic scintillators are **transparent to their own fluorescence emission**
  - Fluorescence **transitions have a lower energy** than **the minimum required for excitation**
  - Little self absorption



Knoll 1999

Organic Scintillators

TYPES OF ORGANIC SCINTILLATORS

- **Pure** organic **crystals**
  - **Anthracene (highest scintillation efficiency)**
  - **Stilbene**
    - Fragile and difficult to obtain in large sizes
    - Directional dependence of scintillation efficiency
- **Liquid** organic solutions
  - Produced by **dissolving an organic scintillator** in an appropriate solvent
    - More resistant to radiation damage effects by intense radiation
- **Plastic scintillators**
  - Organic scintillator dissolved in a solvent that is subsequently **polymerized**
    - Solvent: styrene monomer, polyvinyltoluene, polymethylmethacrylate
    - **Inexpensive, practical choice for large-volume scintillators**

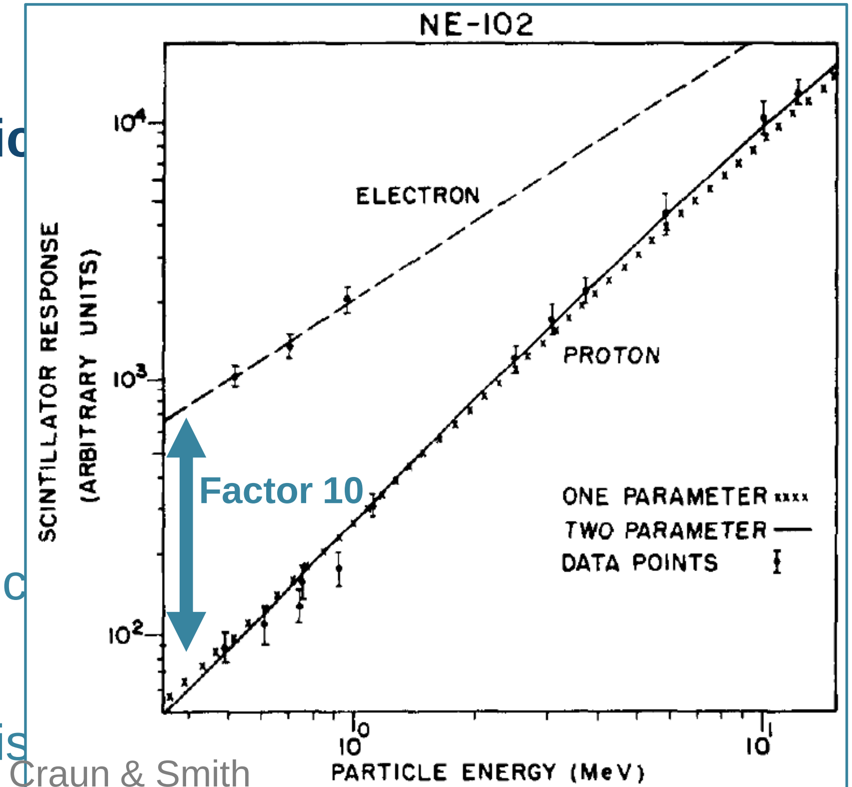
Organic Scintillators

LIGHT YIELD

- **Kinetic energy lost by charged partic**
  - Fluorescent energy
  - Lattice vibrations or heat
- Scintillation **efficiency** depends on
  - Particle type AND energy

➢ Response to **electrons** is linear for partic **energies above ~125 keV**

➢ Response to **heavy charged particles** is always **less for equivalent energies** and is **nonlinear to much higher initial energies**



Craun & Smith 1970

- **Alpha-to-beta ratio**
  Describes the **difference of light output** for an organic scintillator for **electrons and charged particles** of the **same energy**

Organic Scintillators

TIME RESPONSE

- Assuming that luminescent states in an organic molecule are formed instantaneously and only prompt fluorescence is obseved
  - **Time profile** of the light pulse should be a **very fast leading edge** followed by a **simple exponential decay**
    - Yield characterized by the **Decay Time**
- Times of approximately **half a nanosecond** are required to populate the levels from which the prompt fluorescence light arises
  - For very fast scintillators:
    decay time from these levels is only three or four times greater

	τ_1 (rise)	τ(decay)	σ_{ET}	τ	FWHM
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

Performance of ultrafast organic scintillators specified by FWHM time rather than decay time alone

Organic Scintillators

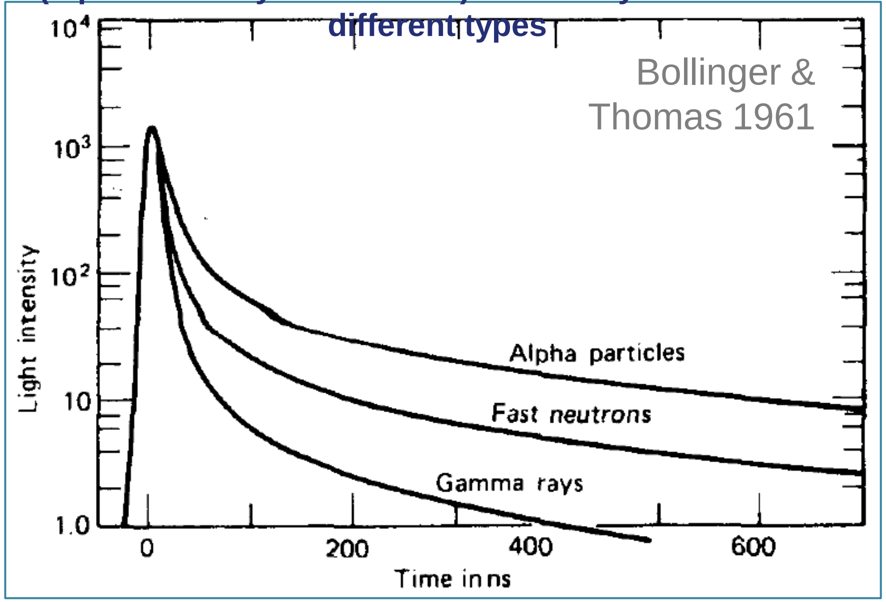
PULSE SHAPE DISCRIMINATION

- Fraction of light in the slow component depends on the **nature of the exciting particle**

  - Discrimination of particles of different kinds that deposit the same energy
in the detector

    ➔ Widely applied to eliminate **gamma-ray-induced events** when organic scintillators are used as neutron detectors

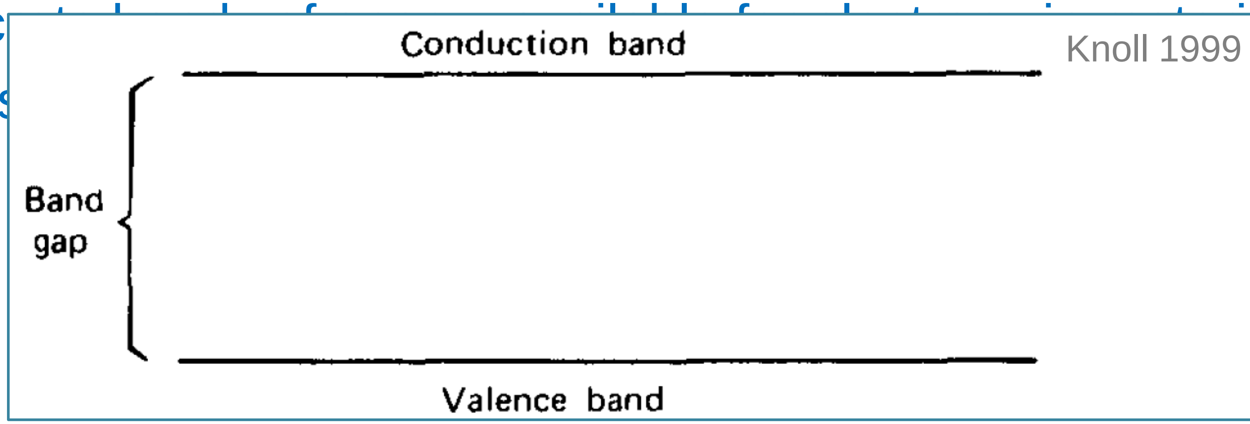
Time dependence of scintillation pulses in stilbene (equal intensity at time zero) excited by radiations of different types



Inorganic Scintillators

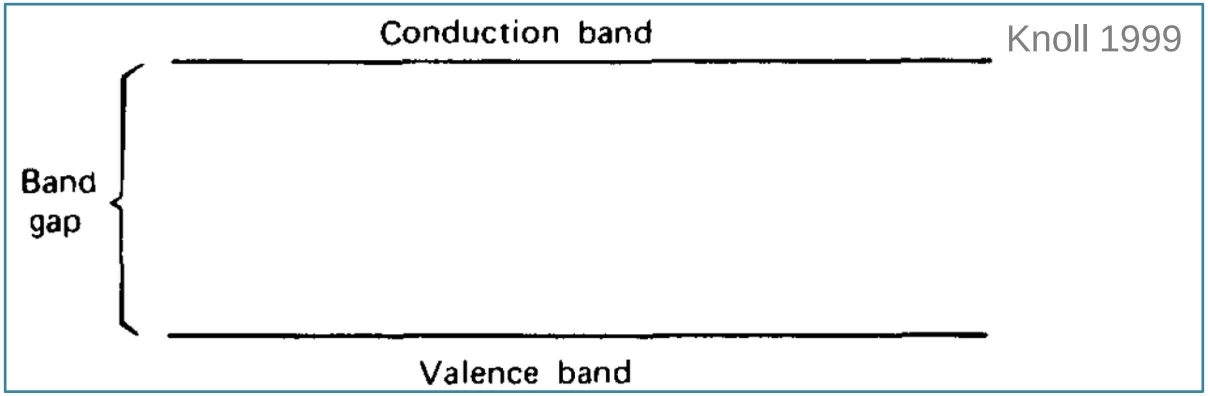
SCINTILLATION MECHANISM IN INORGANIC CRYSTALS WITH ACTIVATORS

- Depends on **energy states** determined by the **crystal lattice** of the material
  - Disc als class



- **Valence band**: Electrons bound at lattice sites
- **Conduction band**: Electrons with sufficient energy to be free to migrate throughout the crystal

Inorganic Scintillators



Knoll 1999

OPERATING MODE

1. **Energy absorption:** Electron in the valence band gets elevated across the gap into the conduction band, leaving a hole in the normally filled valence band

   a) Case of **pure crystal**:

   - **Return of the electron to the valence band** with the emission of a photon
     is an **inefficient process**!
     - Typical **gap widths** are such that the resulting photon would be

Inorganic Scintillators

b) Case of **crystals with activators**:

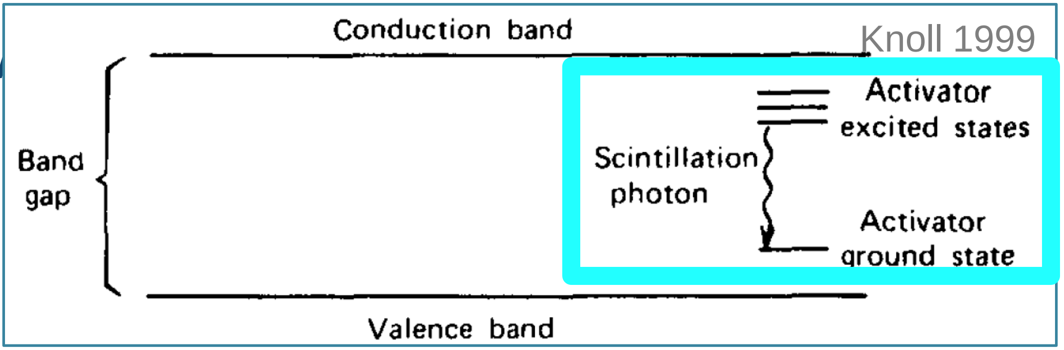
- Impurities added to inorganic scintillators in order to **enhance the probability** of visible photon emission during de-excitation process
  - **Special sites** in the lattice at which the normal energy band structure is modified from that of the pure crystal
    - Luminescence centers or recombination centers
  - Energy states created within the forbidden gap through which the electron can de-excite back to the valence band

    ➔ Energy is less than that of the full forbidden gap
  - Transition can now give rise to a **visible photon** and therefore serve as the basis of the scintillation process

➔ **Activator's energy structure** determines the emission spectrum of the scintillator

Inorganic Scintillators

SCINTILLATION MECHANISM



1. A charged particle passing through the detection medium forms a large number of electron-hole pairs
   - Created by electrons elevated from the valence to the conduction band
2. Positive hole drifts quickly **to the location of an activator site and ionizes it**
   - Ionization energy of the impurity will be **less** than that of a typical lattice site
3. Electron free to migrate through the crystal until it encounters an ionized activator
   - Electron can drop into the activator site, creating a neutral

Inorganic Scintillators

- If activator properly chosen and state is formed in excited configuration :
  - **Transition in the visible energy range**
  - **Typical half-lives of 50 – 500 ns**
    - Migration time for the electron is much shorter!

    ➔ all excited impurity configurations formed essentially at once

Decay time of activator states determines the **time characteristics** of the emitted **scintillation light**

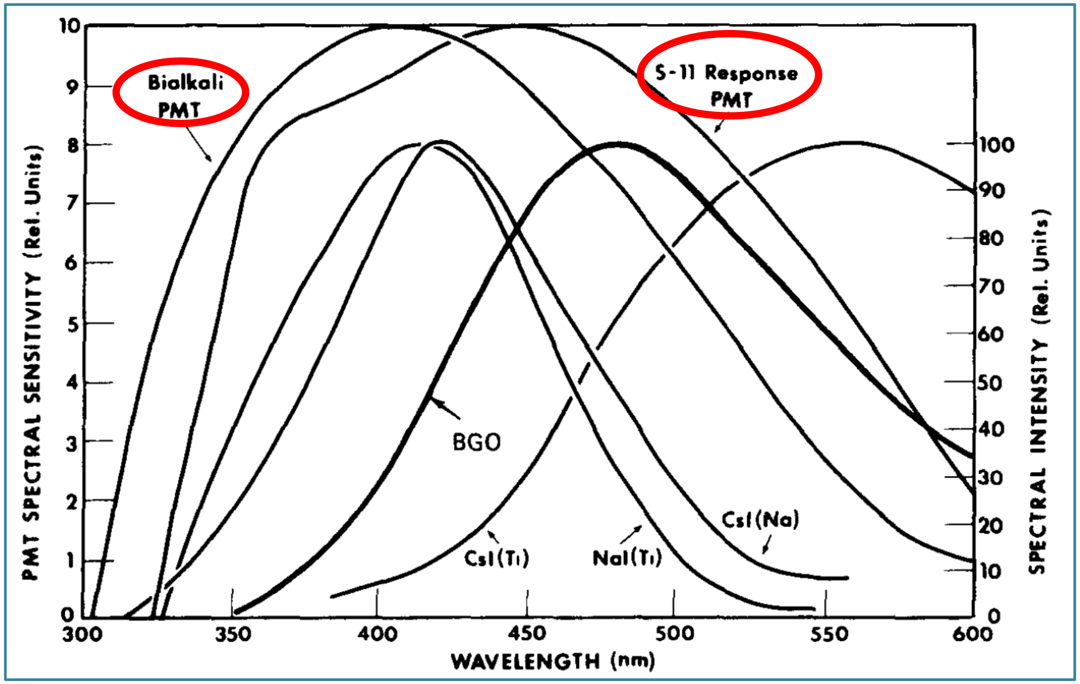
Inorganic Scintillators

COMPETING PROCESSES

1. Electron arrives at impurity site and creates an excited configuration whose **transition to the ground state is forbidden**!
   - State requires **an additional increment of energy to raise** to a higher-lying state from which de-excitation to the ground state is possible
     - **Source of energy: thermal excitation**
     - The resulting **slow component of light** is **phosphorescence**
       - **Source of background light or "afterglow" in scintillators**
2. Electron captured at an activator site
   - **Radiationless transitions between some excited states** formed by electron capture and the ground state
     - **No visible photon results**

Inorganic Scintillators

EMISSION SPECTRUM OF THE LIGHT PRODUCED BY 4 INORGANIC



from Scintillation Phosphor Catalog

- Response curves for two widely used photocathodes
  - To make **full use of the scintillation light**, the spectrum should fall near the wavelength region of maximum sensitivity for the PMTs

Inorganic Scintillators

	Specific Gravity	Wavelength of Max. Emission	Refractive Index	Decay Time (µs)	Abs. Light Yield in Photons/MeV	Relative Pulse Height Using Bialk. PM tube
Alkali Halides						
NaI(Tl)	3.67	415	1.85	0.23	38 000	1.00
CsI(Tl)	4.51	540	1.80	0.68 (64%), 3.34 (36%)	65 000	0.49
CsI(Na)	4.51	420	1.84	0.46, 4.18	39 000	1.10
Li(Eu)	4.08	470	1.96	1.4	11 000	0.23
Other Slow Inorganics						
BGO	7.13	480	2.15	0.30	8200	0.13
$CdWO_4$	7.90	470	2.3	1.1 (40%), 14.5 (60%)	15 000	0.4
ZnS(Ag) (polycrystalline)	4.09	450	2.36	0.2		1.3[a]
CaF_2 (Eu)	3.19	435	1.47	0.9	24 000	0.5
Unactivated Fast Inorganics						
BaF_2 (fast component)	4.89	220		0.0006	1400	na
BaF_2 (slow component)	4.89	310	1.56	0.63	[illegible]	[illegible]
CsI (fast component)	4.51	305		0.002 (35%), 0.02 (65%)	[illegible]	[illegible]
CsI (slow component)	4.51	450	1.80	multiple, up to several µs	[illegible]	[illegible]
CeF_3	6.16	310, 340	1.68	0.005, 0.027	[illegible]	[illegible] to 0.05
Cerium-Activated Fast Inorganics						
GSO	6.71	440	1.85	0.056 (90%), 0.4 (10%)	9000	0.2
YAP	5.37	370	1.95	0.027	18 000	0.45
YAG	4.56	550	1.82	0.088 (72%), 0.302 (28%)	17 000	0.5
LSO	7.4	420	1.82	0.047	25 000	0.75
LuAP	8.4	365	1.94	0.017	17 000	0.3
Glass Scintillators						
Ce activated Li glass[b]	2.64	400	1.59	0.05 to 0.1	3500	0.09
Tb activated glass[b]	3.03	550	1.5	~3000 to 5000	~50 000	na
For comparison, a typical organic (plastic) scintillator:						
NE102A	1.03	423	1.58	0.002	10 000	0.25

More than one decay component

Inorganic Scintillators

COMPARISON WITH ORGANIC SCINTILLATORS

- Light yield is **more nearly proportional** to deposited radiation energy
  - Quenching processes still lead to some nonlinearity, but to **lesser extent**

- Variance in the light yield for different types of particles of equal energy is also observed
  - **Alpha-to-beta ratio**
    - ~0.66 for NaI(T1) and CsI(T1))
    - ~0.20 for oxide-based materials such as BGO

Alkali Halide Scintillators

Inorganic compounds with the chemical formula MX

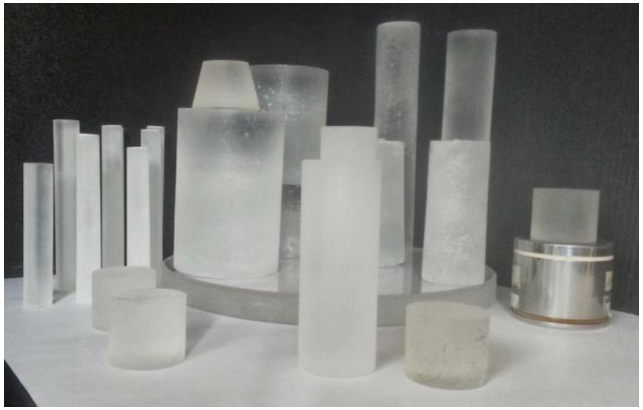
- M is an alkali metal
- X is a halogen
    - Sodium Iodide
    - Cesium Iodide
    - Lithium Iodide

Wikipedia

		Alkali Metals				
		Lithium	**Sodium**	**Potassium**	**Rubidium**	**Caesium**
Halogens	**Fluorine**	LiF (3.0)	NaF (3.1)	KF (3.2)	RbF (3.2)	CsF (3.3)
	Chlorine	LiCl (2.0)	NaCl (2.1)	KCl (2.2)	RbCl (2.2)	CsCl (2.3)
	Bromine	LiBr (1.8)	NaBr (1.9)	KBr (2.0)	RbBr (2.0)	CsBr (2.1)
	Iodine	LiI (1.5)	NaI (1.6)	KI (1.7)	RbI (1.7)	CsI (1.8)

Numbers beside the compounds show the electronegativity difference between the elements based on the Pauling scale. The higher the number is, the more the compound attracts electrons towards it

NaI(Tl) Scintillators



®Marketec

- Crystalline sodium iodide with a trace of thallium iodide

➔ Studied since 1950

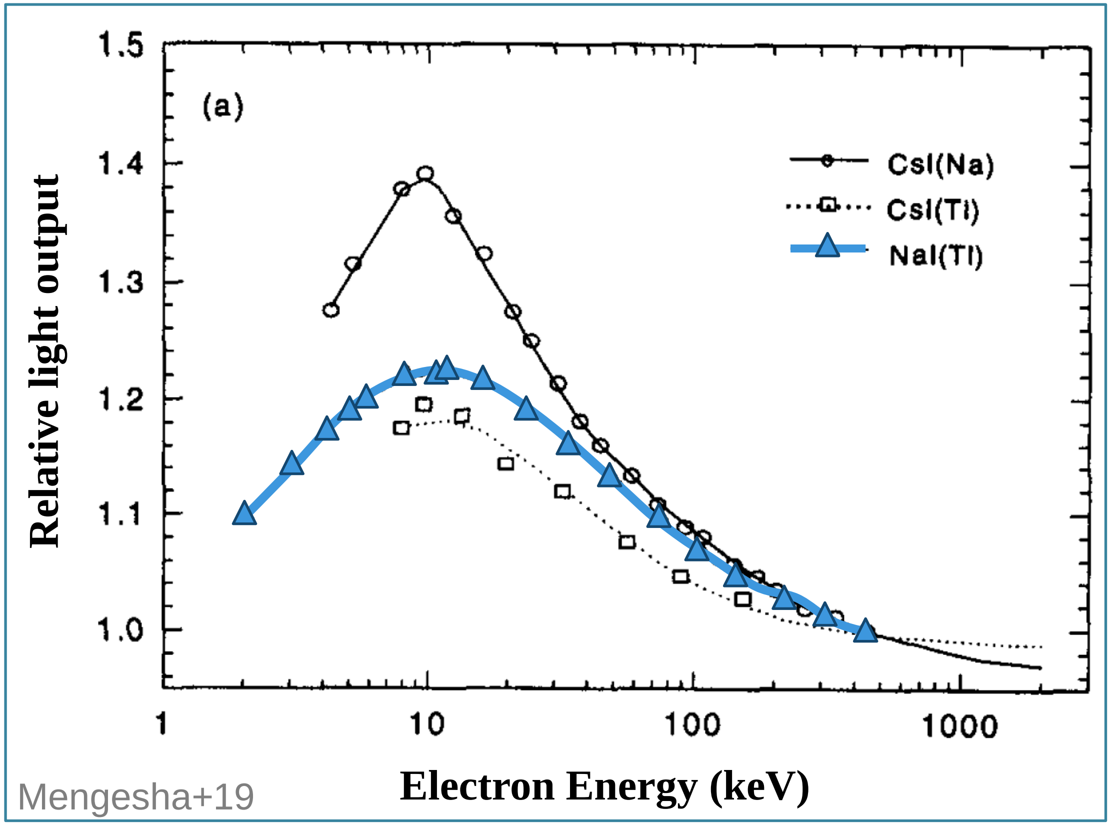
- PROs:
  - Exceptionally **large scintillation light output** compared with the organic materials
  - Can be machined into a large variety of sizes and shapes
- CONs:
  - Hygroscopic crystal, will deteriorate due to water absorption if exposed to the atmosphere for any length of time

    ➔ Needs to be sealed in air-tight containers
  - Fragile, can be easily damaged by mechanical or thermal shock

NaI(Tl) Scintillators

- **Relative scintillation response** per unit energy deposited for fast electrons plotted as a function of energy for 3 scintillation materials
  - Curves normalized to unity at 445 keV

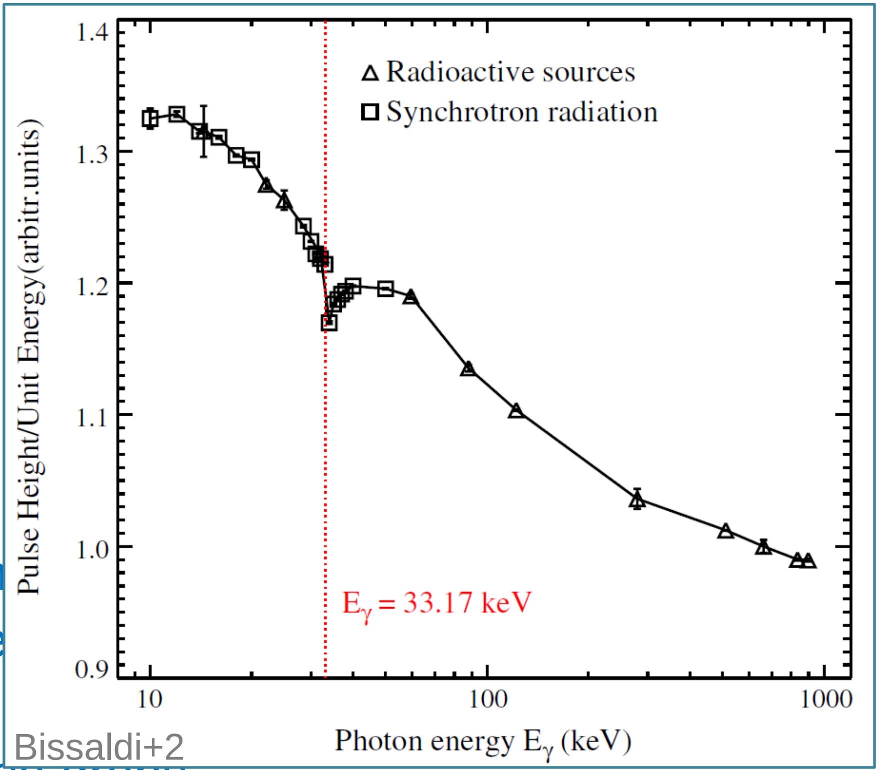
Departure from proportionality at low energy



Mengesha+1998

NaI(Tl) Scintillators

- The **differential linearity** measured for Fermi–GBM NaI(Tl) FM 04, normalized to unity at 661.66 keV



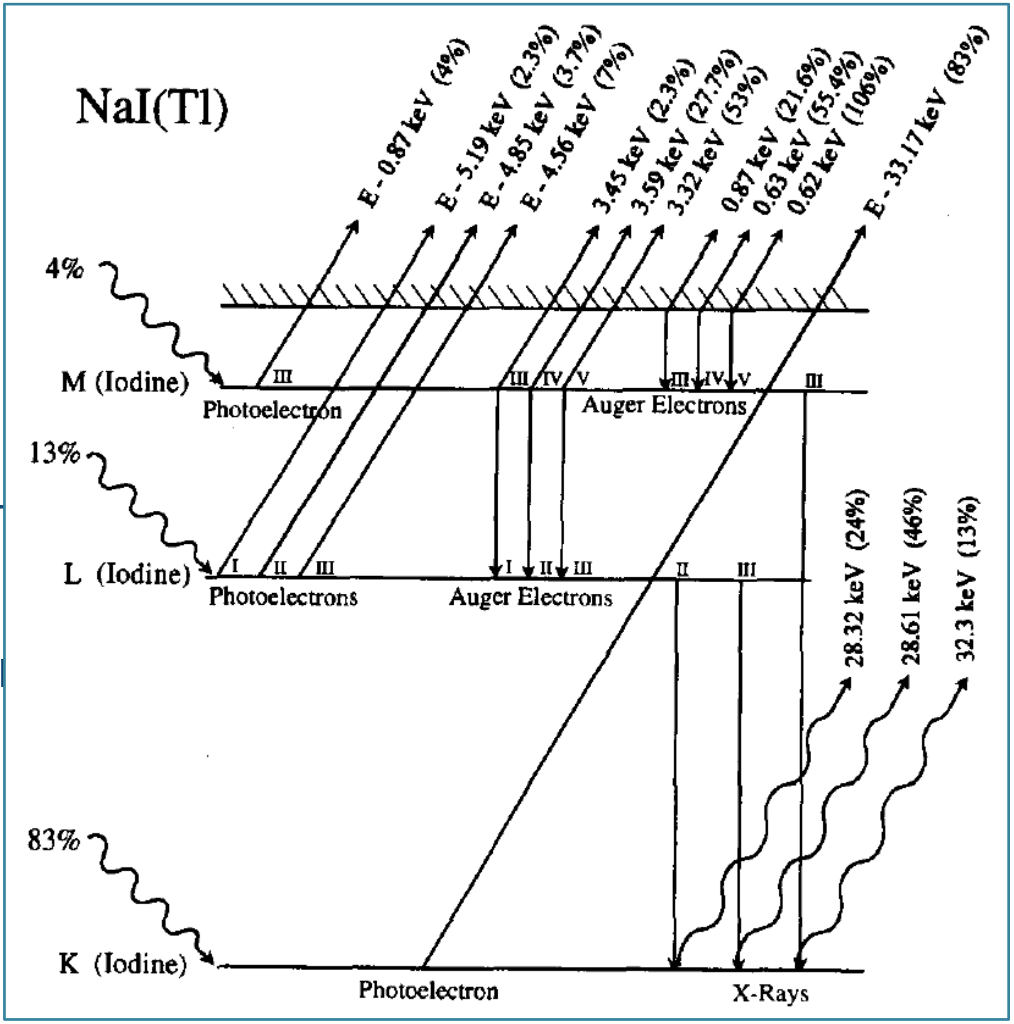
Bissaldi+2009

- Dip at a characteristic energy corresponding to the K-shell binding energy in Iodine, i.e. 33.17 keV
  - Photoelectrons ejected by incident gamma-rays just above the K-shell absorption edge have very little kinetic energy, so that the response drops.
  - Below this energy, K-shell ionization is not possible and L-shell ionization takes place
    - Binding energy is lower: the ejected photoelectrons are more energetic, which causes a rise in the response

NaI(Tl) Scintillators

- The detailed yields of these secondary electrons changes abruptly at the K-shell absorption energy

- Possible origins of electrons an photons following the photo-electric absorption of an incide X-ray or gamma ray with energy E that is above the K-shell binding energy of 33.17 keV



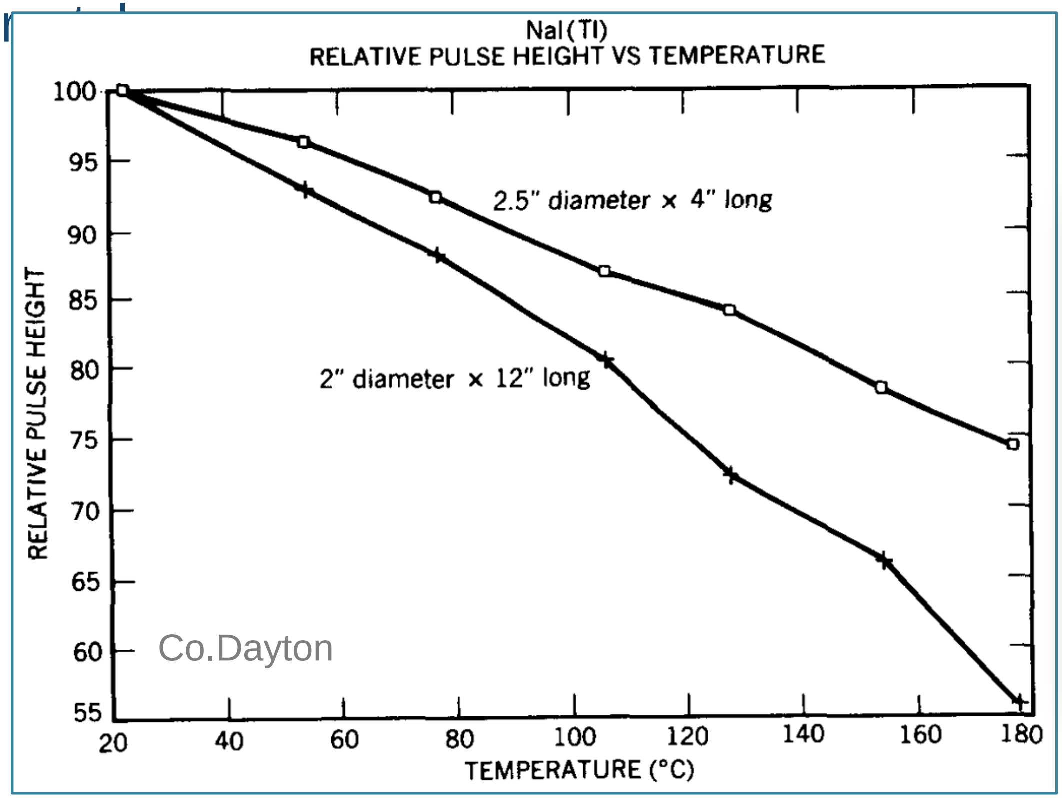
Rooney & Valentine 1997

NaI(Tl) Scintillators

- Dominant decay time of scintillation pulse: **230 ns**
  - Too long for some fast timing or high counting rate applications
  - Phosphorescence with characteristic 0.15 s decay time has also been measured, which contributes about 9% to the overall light yield
  - Other longer-lived phosphorescence components have also been measured
  - At high counting-rates, the phosphorescence will tend to build up due to the multiple overlap from many preceding pulses. This afterglow is often an undesirable characteristic of sodium iodide used in high-rate applications

NaI(Tl) Scintillators

Temperature dependence of the light yield measured from two NaI(Tl) crystals

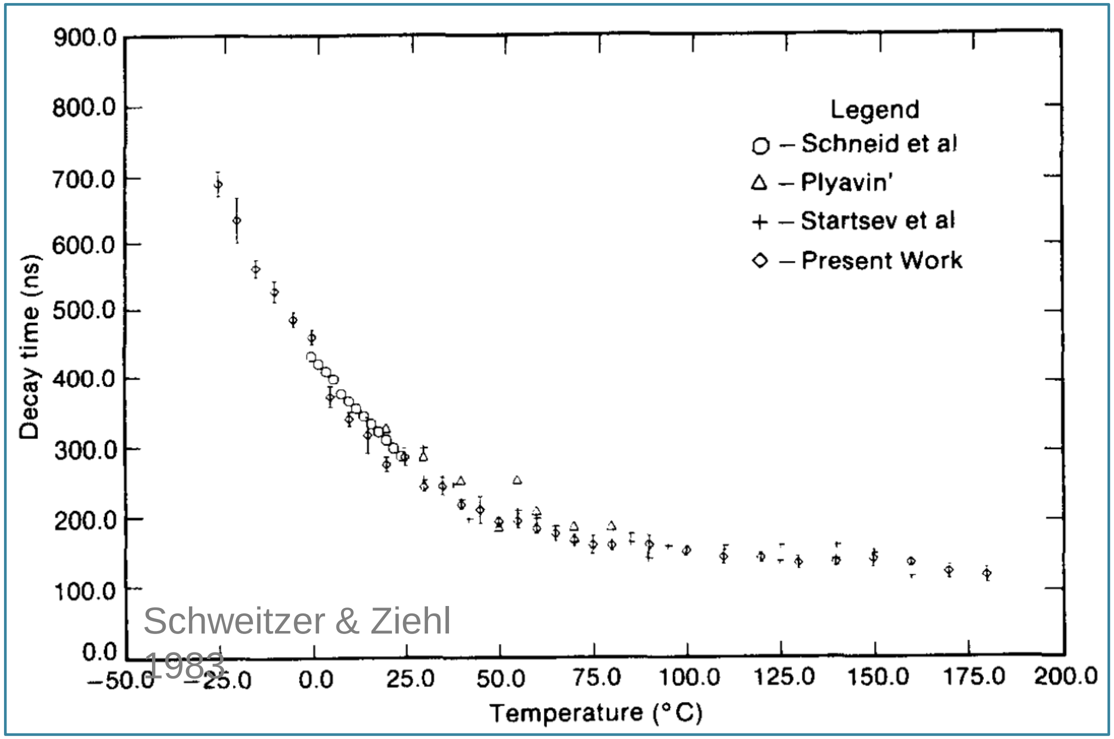


Dropoff in scintillation yield with increasing temperature →generally **poorer energy resolution** when the scintillator must be used **at elevated temperatures**

- difference in behavior between the two crystals probably due to changes in surface reflectivity

NaI(Tl) Scintillators

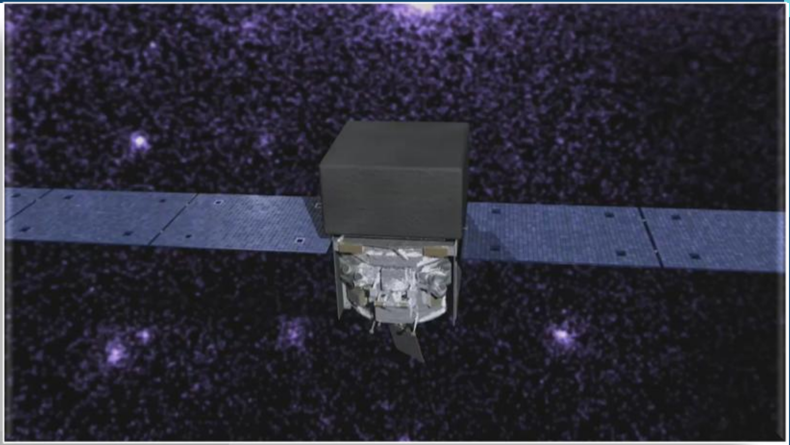
- **Temperature dependence** of the scintillation **decay time** in NaI(T1)
  - **Faster response at higher temperatures**

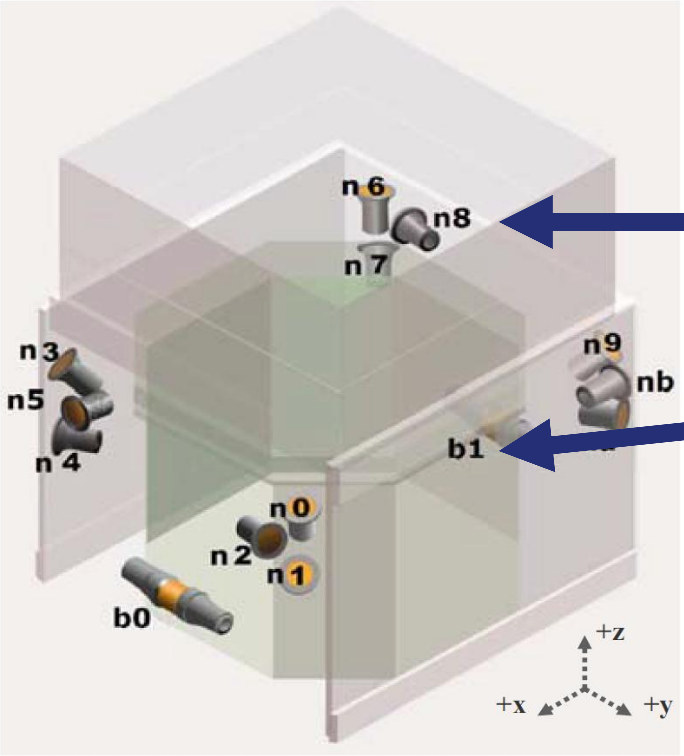


Schweitzer & Ziehl 1983

The Fermi Observatory

- The Gamma-Ray Burst Monitor (GBM) onboard the Fermi observatory
  - Launch June 11, 2008
  - 14 scintillation detectors



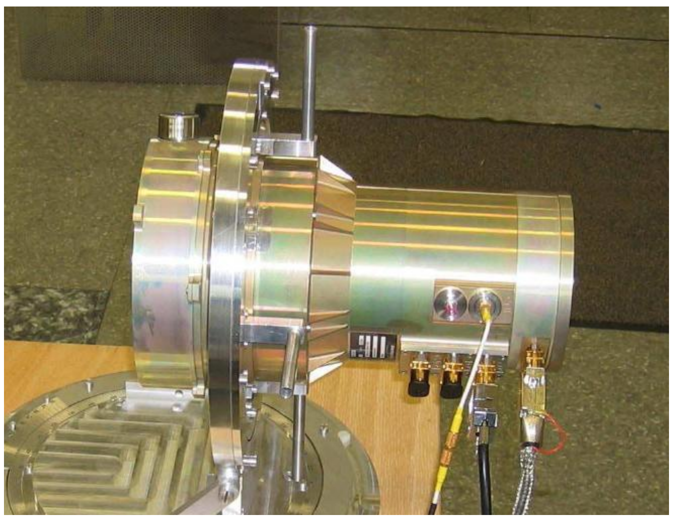


12 NaI(Tl)

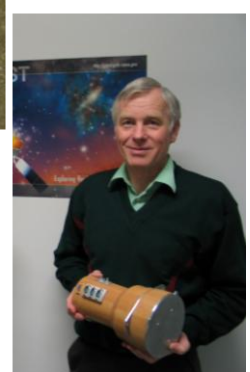
2 BGO

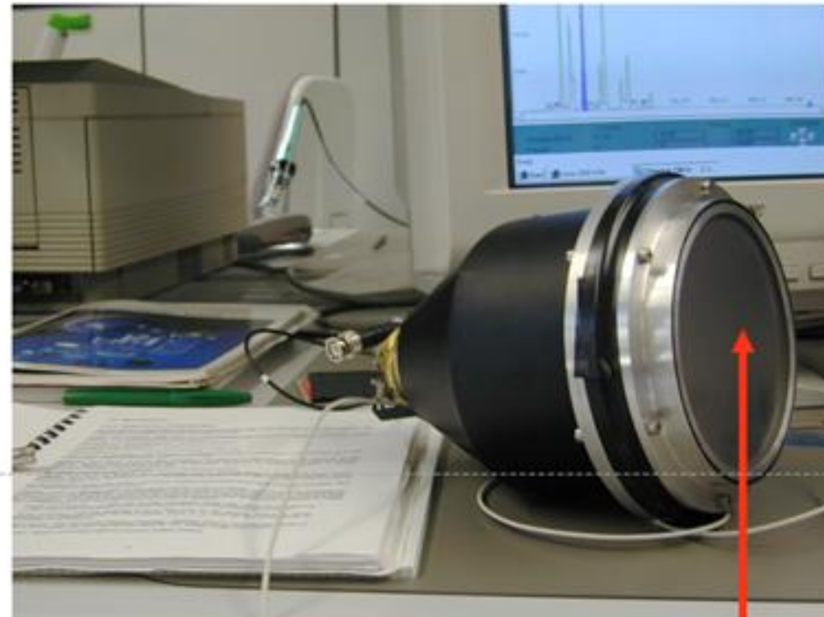
Fermi–GBM NaI(Tl) Scintillators

- 12 NaI(Tl) detectors:
  - Diameter: 12.7 cm (5”)
  - Thickness: 1.27 cm (0.5”)
  - Energy range: 10 keV – 1 MeV

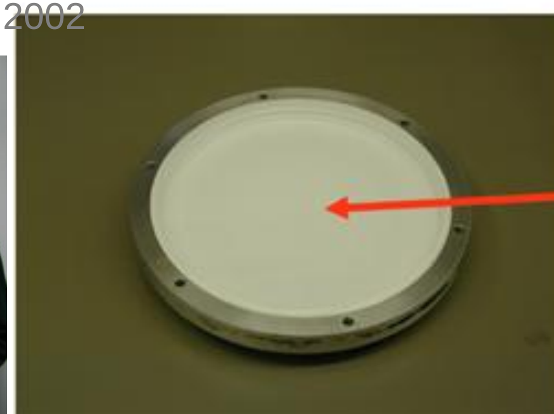


NaI(Tl) detector FM04
@MPE 2005



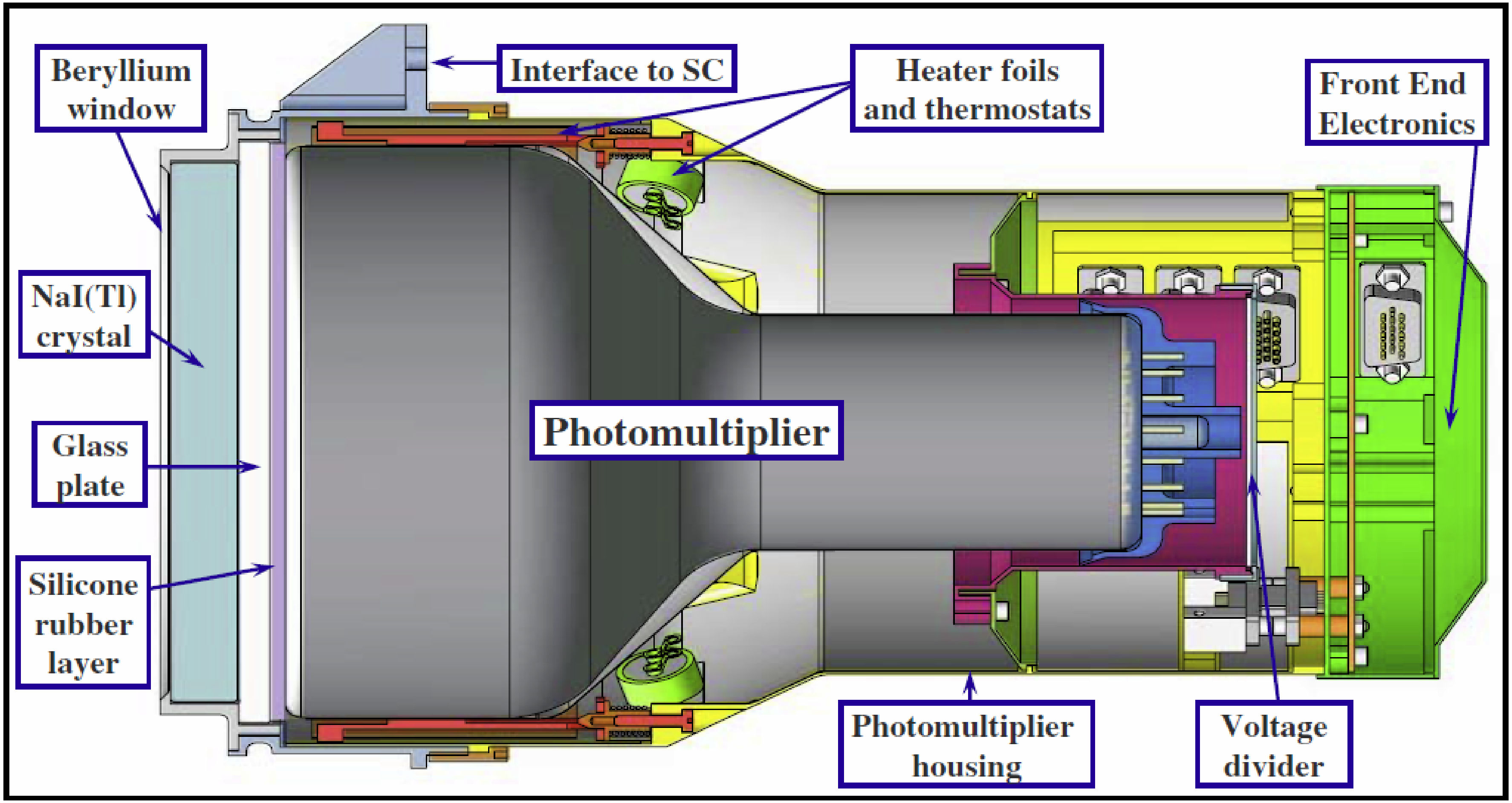


Breadboard crystals @MPE
2002



NaI(Tl)

Fermi–GBM NaI(Tl) Scintillators



Bissaldi+2009

CsI(Tl) Scintillators

Comparison with NaI(Tl)

1. Larger gamma-ray absorption coefficient per unit size compared to NaI(Tl)
   - Important for applications where size and weight are crucial (space missions)
2. Less brittle
   - Can resist more severe conditions of shock and vibration
3. Less hygroscopic
   - Will still deteriorate if exposed to water or high humidity

Other characteristics

- Reasonably soft and malleable (various shapes)
- Variable decay time for various exciting particles
  - Pulse shape discrimination techniques can therefore be used to differentiate among various types of radiation
  - Particularly clean separations can be achieved between charged particles and electron events.

CsI(Tl) Scintillators

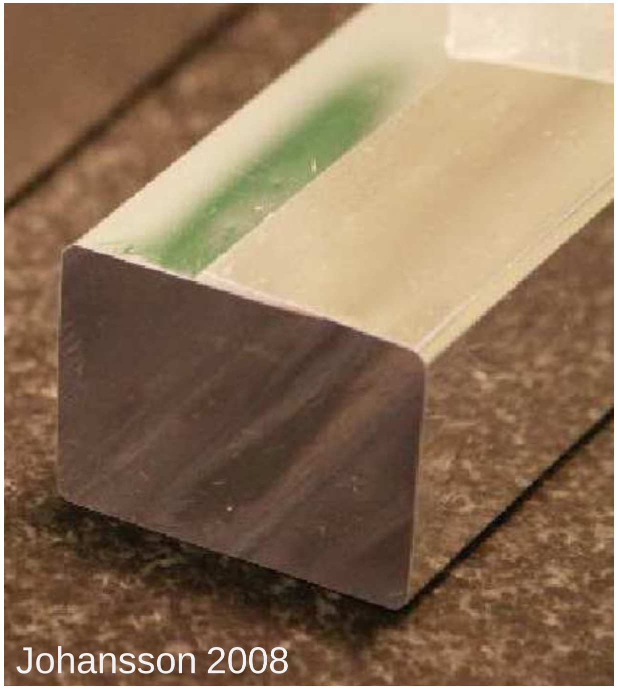
Other characteristics

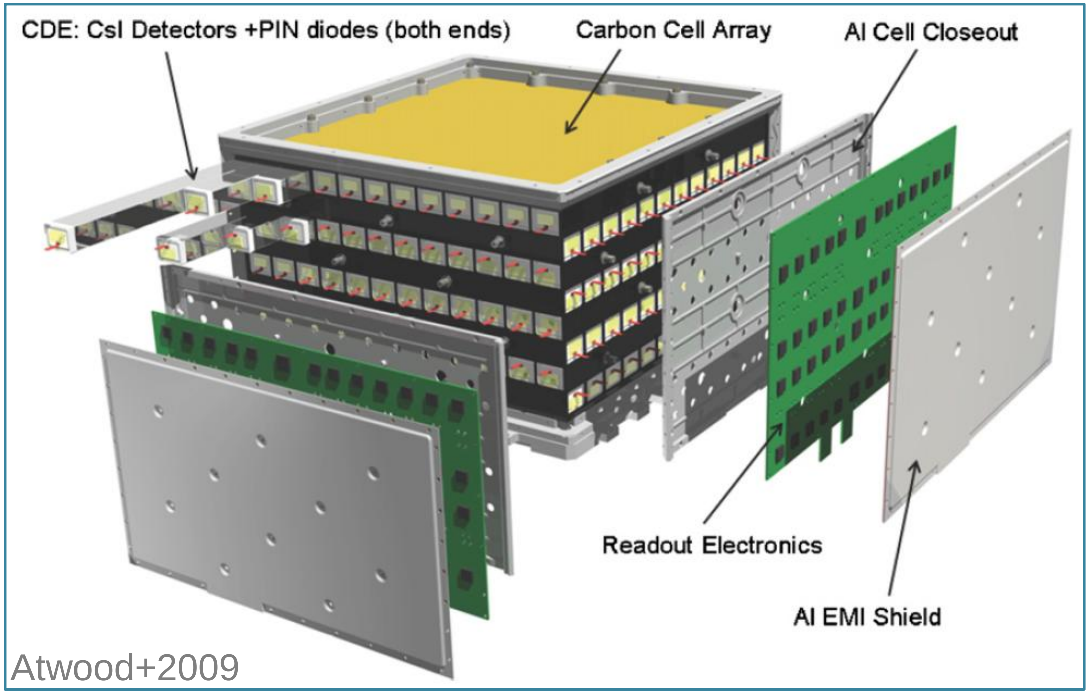
- Emission spectrum peaked at a **much longer wavelength**
  - **Poorly matched** to the response of PMTs **with bialkali photocathodes**
    - Light output often quoted as being substantially lower
  - BUT: If **matched to photodiodes** with extended response into the red region of the spectrum, scintillation yield is **actually higher**

- The luminescent states in CsI(T1) are populated through an exponential process
  - Unusually **long rise time of 20 ns** for the initial appearance of the light

Fermi-LAT CsI(Tl) Calorimeter

- Calorimeter with 96 CsI(Tl) crystals
  - Crystal size: 2.7cm × 2.0 cm × 32.6 cm
  - Arrangment: 8 layers of 12 crystals
    - Each layer is aligned 90° with respect to its neighbors, forming an (x, y) (hodoscopic) array

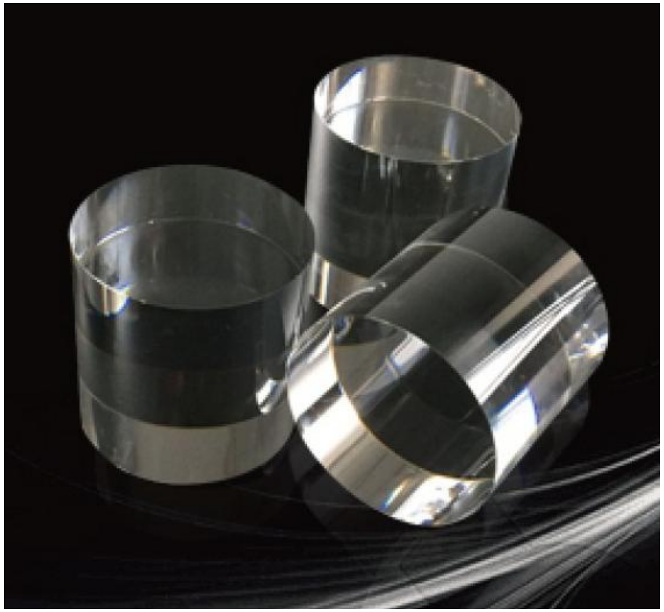


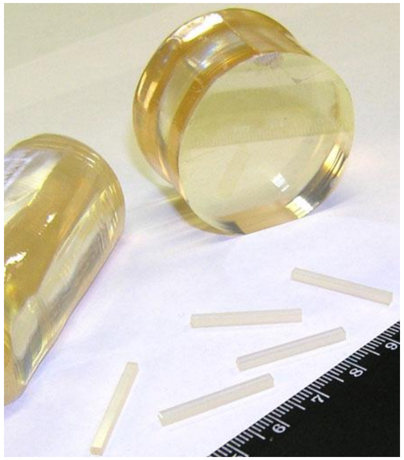


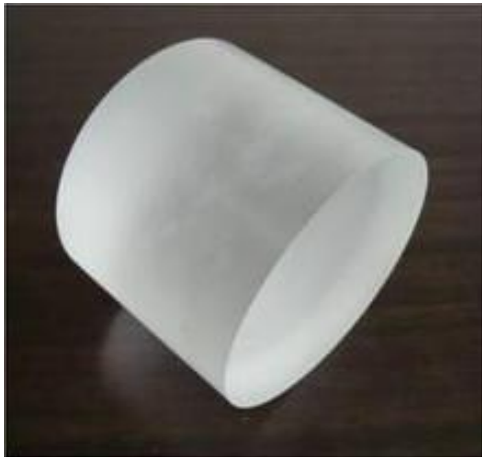
Other «slow» Inorganic Crystals

Some examples

- Bismuth Germanate ($Bi_4Ge_3O_{12}$)
- Cadmium Tungstate ($CdWO_4$)
- Zinc Sulfide (ZnS(Ag))
- Calcium Fluoride (CaF_2)





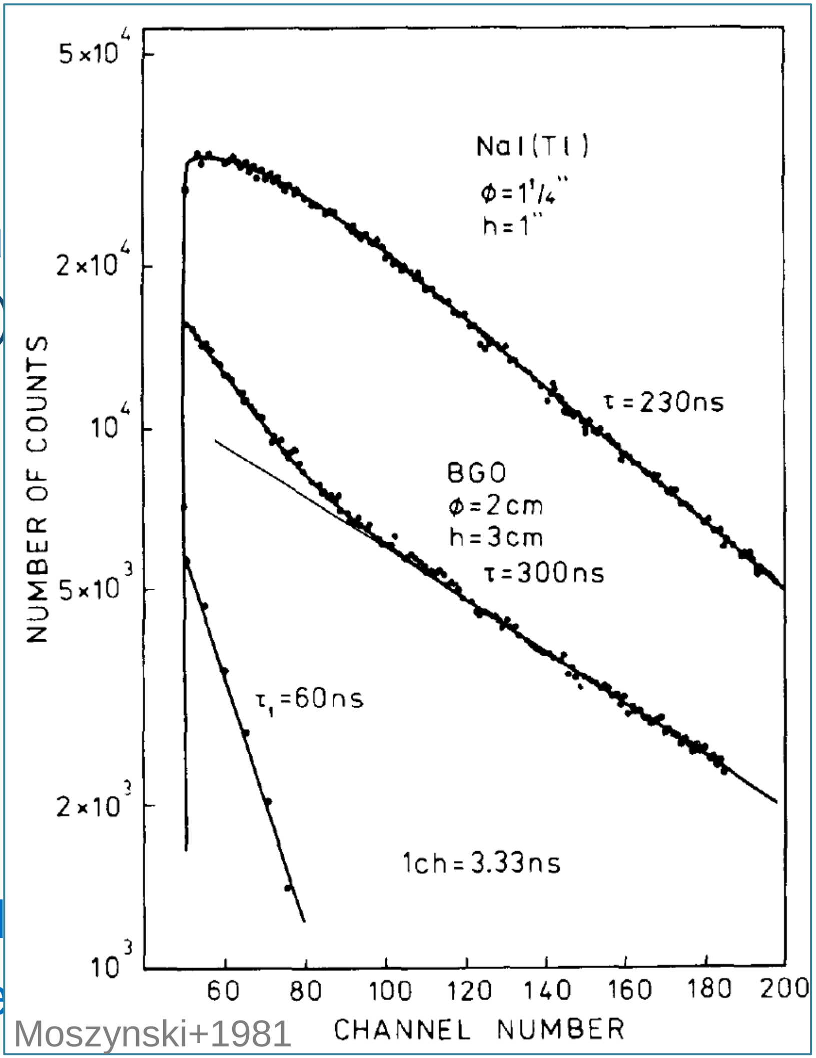


BGO Scintillators

- **Major advantage**
  - High density (7.13 g/cm3) and large atomic number (83)
    - ➔ Largest probability per unit volume of any commonly available scintillation material for the **photoelectric absorption** of gamma rays
  - **Easy to handle and use**
- **Other characteristics**
  - **Light yield relatively low** (10-20% of that of NaI(Tl))
  - High refractive index (2.15)
    - Collection of the light **more difficult**
    - ➔ Primary interest when the need for **high gamma-ray counting efficiency outweighs considerations of energy resolution**

BGO Scintillators

Time profile of the light emitted in a scintillation event in BGO and



Moszynski+1981

- BGO overall **timing resolution is abou a factor of 2 worse** than that for NaI(Tl)
- BUT: BGO shows **no long decay components that lead to afterglow** in NaI(Tl)
  - application in X-ray computed tomography scanners where scintillators operated in current mod must accurately follow rapid change in X-ray intensity

BGO Scintillators

Other characteristics

- **Pure inorganic scintillator, does not require activators**
  - Luminescence associated with an optical transition of the Bi^{3+} ion
    - Large shift between optical absorption and emission spectra

    ➔**little self-absorption** of the scintillation light

- Scintillation **efficiency** depends strongly on **the purity of the crystal**

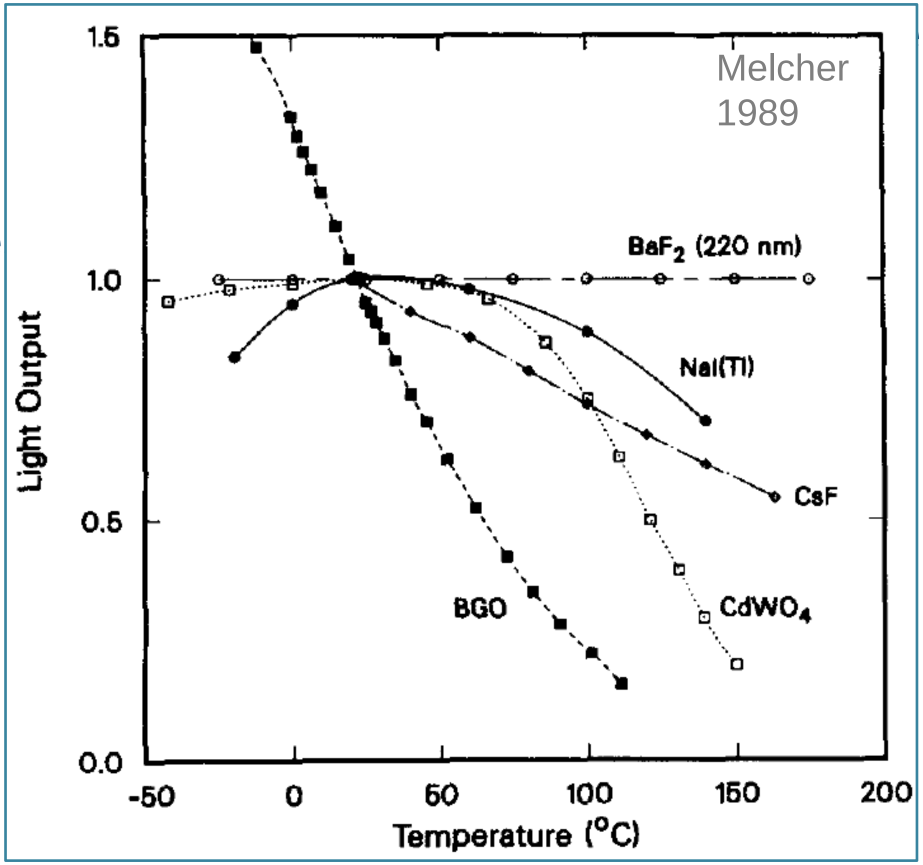
- BGO remains two to three times **more costly** than NaI(Tl) and is available only in **limited sizes**

BGO Scintillators

Light output of some common scintillators as a function of

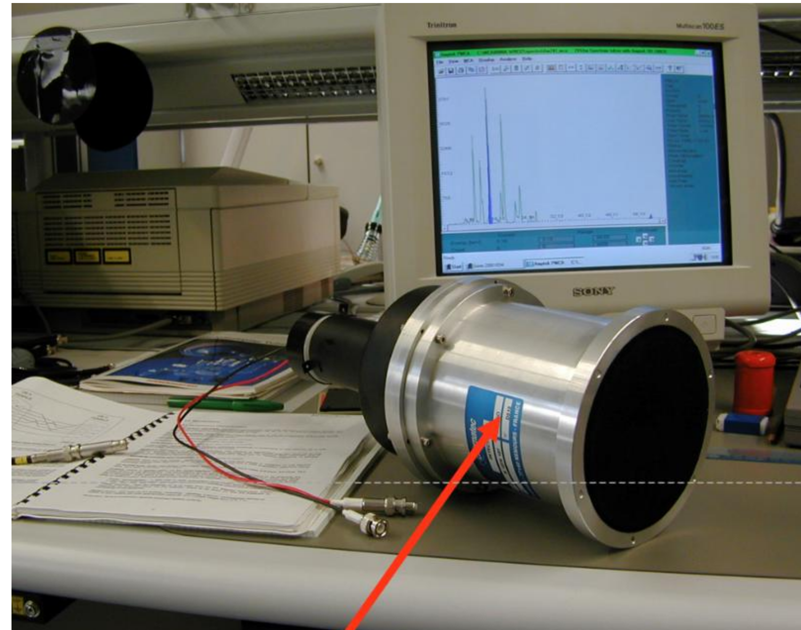
- **Light output** from BGO **decrease** with **increasing temperature**

- Since the light yield is already low at room temperature, its rapid dropoff severely limits the usefulness of BGO in high-temperature applications



Fermi–GBM BGO Scintillators

- 2 BGO detectors:
  - Diameter: 12.7 cm (5”)
  - Thickness: 12.7 cm (5”)
  - Energy range:
    250 keV – 40 MeV

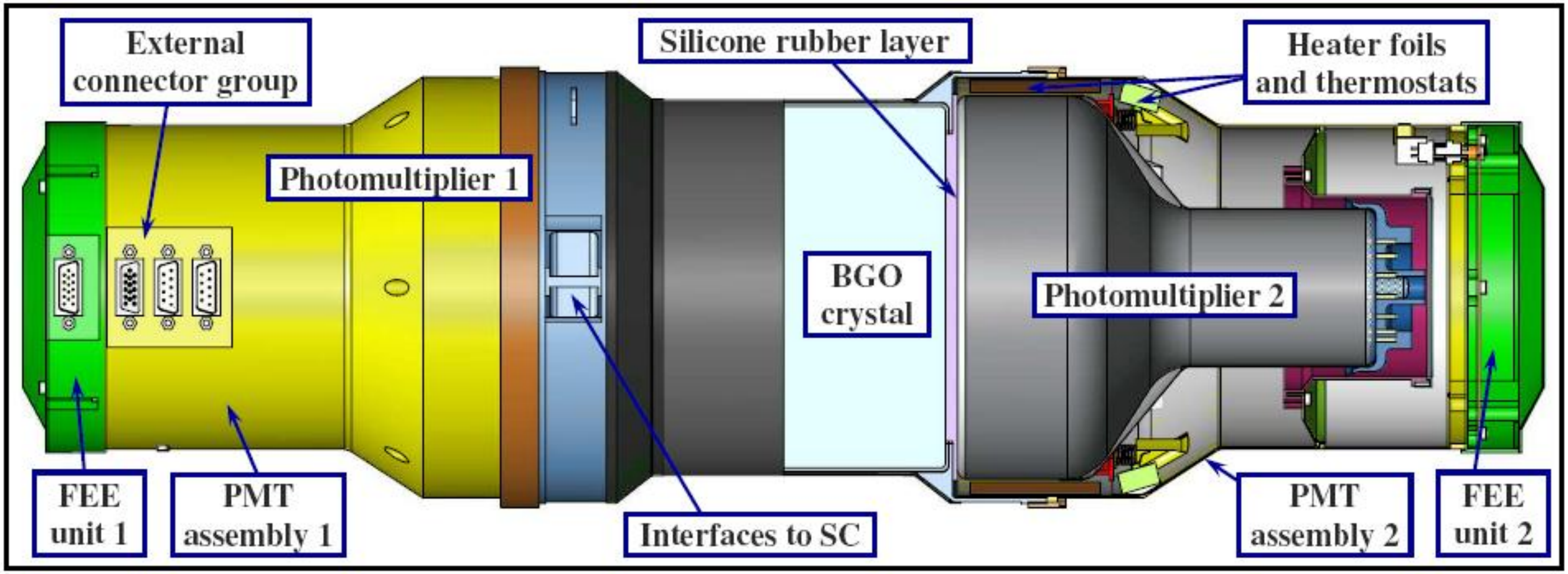


BGO detector FM01 @MPE 2005

BGO

Breadboard crystals @MPE 2002

Fermi–GBM BGO Scintillators



Bissaldi+2009

Other Inorganic Scintillators

1. **Unactivated Fast Inorganics with Low Light Yield**
   - Fast component in the scintillation decay
     - **Decay time as fast as 1 ns**
   - Examples
     - Barium Fluoride, Pure Cesium Iodide, Cerium Halides, Lead Tungstate
2. **Cerium-Activated «Fast» Inorganics**
   - Reasonably good light yield, decay time of the cerium luminescence ranges from about **20 to 80 ns**: intermediate position between fast organics (few ns) and inorganics (several hundred ns)
   - Examples
     - Rare Earth Oxyorthosilicates, Lanthanoid Pyrosilcates, Rare Earth Aluminium Perovskites, Rare Earth Aluminium Garnets, Lanthanium Halides, Lutetium Halides, Other Halides,

Other Inorganic Scintillators

3. **Transparent Ceramic Scintillators**
   - Sintering nanocrystals into polycrystalline solids
   - Good light output, absence of long afterglow, resistence to damage
   - Operated in current mode, very long time decay (hundreds of μs)
4. **Glass Scintillators**
   - Silicate glasses containing lithium and activated with cerium
   - Widely used as **neutron detectors** or in **imaging applications**
   - Relative light output is quiet low, intermediate decay time
   - Can be **operated at high T** and under **bad environmental conditions**
   - May contain naturally radioactive thorium: **spontaneous background**
5. **Noble Gas Scintillators**

Radiation damage effects in Inorganic Scintillators

- **DAMAGE**: Reduction in the **transparency of the scintillator**
- Causes:
  - Creation of color centers that absorb the scintillation light
  - Interferences in the processes
  - Presence of oxygen contamination leading to the formation of hydroxyl species in the alkali halides
  - Structural defects in oxide scintillators
- Effects:
  - **Long-lived light emission** in the form of **phosphorescence**
    - Can be rate dependent and vary greatly with the type of radiation involved in the exposure
  - Often **partially reversible**
- The most sensitive compounds appear to be the thallium-activated alkali halides for which exposures of 10 Gy can be significant

Light collection and Scintillator Mounting

- **Goal:** To collect the **largest possible fraction of the light emitted isotropically** from the track of the ionizing particle
- **Obstacles:**
  1. Optical self-absorption within the scintillator
     - Usually not significant
  2. Losses at the scintillator surfaces
     - Conditions at the **interface** between the **scintillator and the container** in which it is mounted affect the collection uniformity

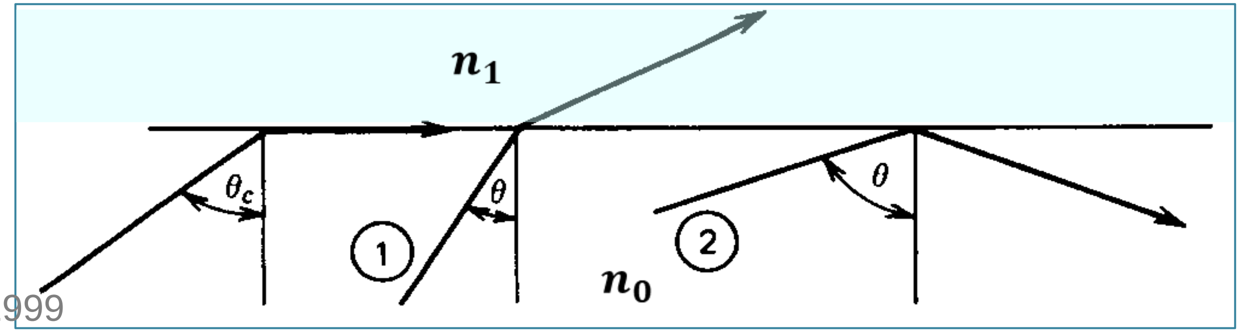
Light collection CONDITIONS affetct the **ENERGY RESOLUTION** of a scintilator

If the **number** of scintillation photons is **reduced**, the **statistical broadening** of the response function gets **worse**

Uniformity of light collection determines the **variation of signal pulse amplitude**

Light collection and Scintillator Mounting

- Scintillation light emitted **isotropically** in all directions
  - **Only a fraction travels directly to the PMT**
  - To collect the rest: one or more **reflections** at the scintillators surfaces
- Critical angle $\theta_c = \sin^{-1}\frac{n_1}{n_0}$
  - n_0: Refractive index of scintillator
  - n_1: Refractive index of surrounding medium
    1. If $\theta < \theta_c$: Partial or «Fresnel» reflection and partial transmission through the surface
    2. If $\theta > \theta_c$: Total internal reflection (TIR)



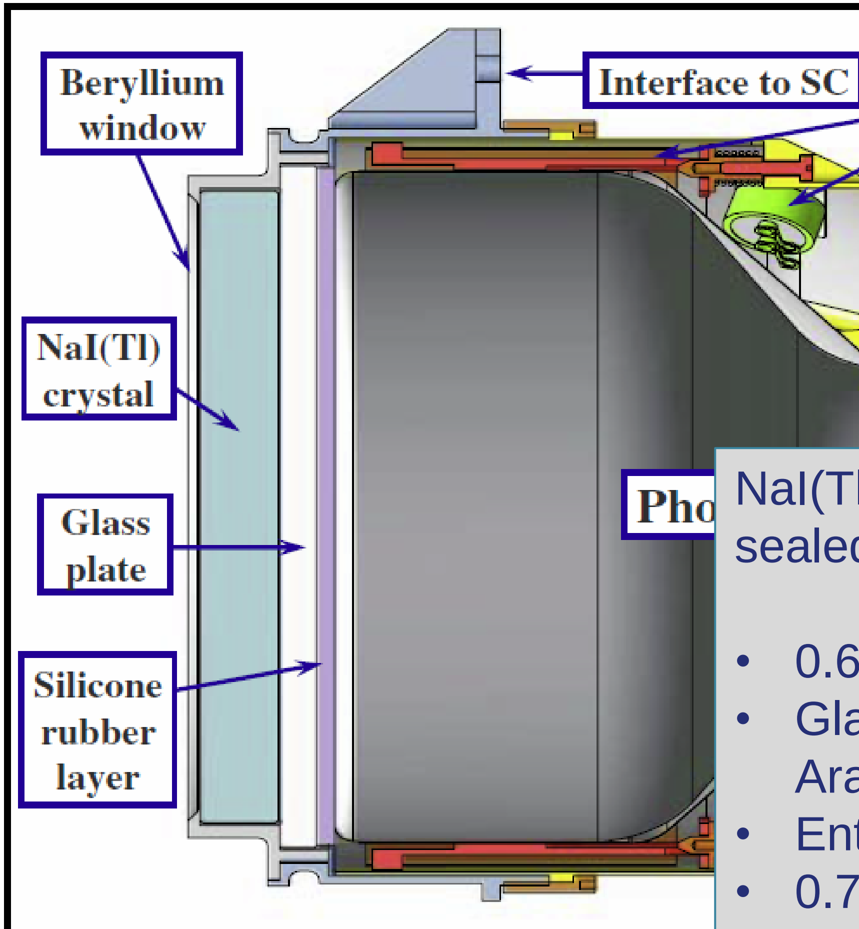
Knoll 1999

Light collection and Scintillator Mounting

- Scintillator surrounded by a **reflector at all surfaces** except the one to the PMT in order to maximize total internal reflection
  - Specular or diffuse reflectors (**magnesium or aluminium oxide**)

- At the PMT: Internal reflection has to be minimized
  - Ideally: optically coupling of the scintillator through a transparent medium of the same index of refraction as the scintillator
    - NaI and BGO have high refractive index: internal reflection will occur inevitably

- **Shield from external light**
    - Crystals canned in metallic **containers +** hermetically **sealed**
    - Surface through which the light is collected: **glass or quartz window**



Bissaldi+2009

NaI(Tl) scintillators are packed in a hermetically sealed **light-tight aluminum housing**

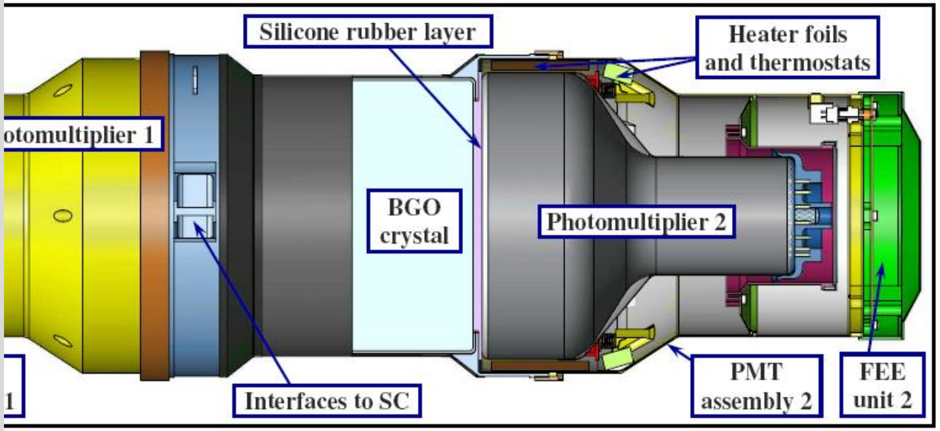
- 0.6 cm thick glass window
- Glass glued to the Al housing with white Araldit
- Entrance window: 0.2 mm thick Be sheet
- 0.7 mm thick silicone in front of the crystal
- Crystal is packed in a reflective white cover of Tetratec (on the front-window side) and Teflon (on the circumference).

Light collection and Scintillator Mounting

- Light collection in large scintillators can often be enhanced by the use of **more than one photomultiplier tube**
  - By providing more than one escape surface
    → Average number of reflections required for a typical event to reach a photomultiplier tube will be less
  - The fewer the reflections, the **greater the light collection efficiency**, and consequently the **greater uniformity of pulse**

BGO crystals polished to **mirror quality** at the glass side windows, while the cylindrical surface
is roughened in order to guarantee a diffuse reflection of the generated photons

- Crystals packed in a carbon-fibre reinforced plastic (CFRP) housing that is held on both sides by titanium rings
  - CFRP provides light tightness and mechanical stability
  - Titanium's thermal expansion coefficient is close to the BGO one



Bissaldi+ 2009