

Introduction to gamma detectors and their applications

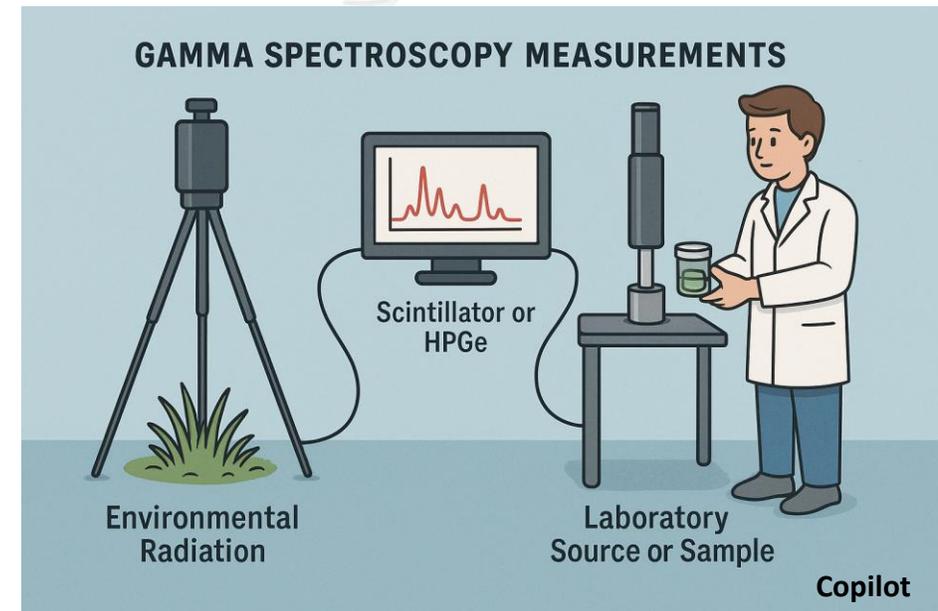
CAEN Winter School 2026

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[Erica Fanchini](#)



- Data acquisition chain
- Detectors:
 - Scintillators
 - Organic
 - Inorganic
 - Semiconductors
- Data acquisition
- Gamma interactions
- Detector response comparison



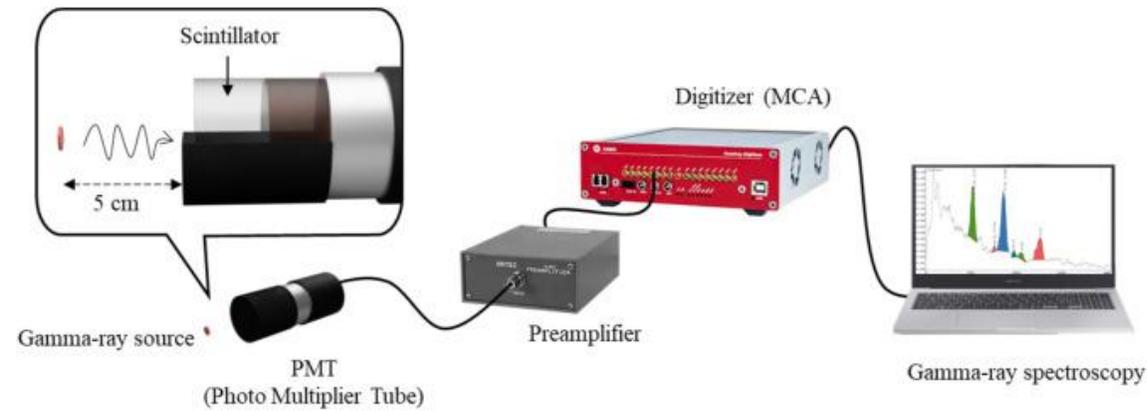
Particle detection works by counting or measuring the energy of the incoming particle or gamma ray using a detector.

- The initial stage is to **detect the particle interaction** using an appropriate detector
- The detector provides a signal due to the interacting particle into the material
- The detector signal is converted into **electrical signal** (if not done by the detector itself)
- In a spectroscopic system the signal output is proportional to the energy of the particle released into the detector. The derived **energy spectrum** depicts the **distribution of particle intensity as a function of energy**.

For gamma spectroscopy application the gamma spectrum is characteristic of the gamma-emitting nuclides contained in the source.

- The spectrum is a visual depiction of the various energy levels found in gamma-ray emissions.
- The observed energy levels are compared to the known energies of gamma-rays emitted by radioisotopes, and the identity of the emitter can be determined.

- The basic components are:
 - **DETECTOR**, which collects the energy deposition of the incoming radiation and produces a voltage signal proportional to the energy
 - **ANALOG-TO-DIGITAL CONVERTER (ADC)**, to convert voltage signal into a digital number
 - **MULTI-CHANNEL ANALYZER (MCA) or DIGITIZER**, to bin the numbers into the spectrum
 - **COMPUTER**, to compare spectra of known isotopes and try to identify radioactive material
- Additional components may include signal amplifiers, rate meters, peak position stabilizers, and data handling devices.
- Currently the acquisition can be managed by a single electronic device which simplifies the acquisition chain.



Gamma spectroscopy detectors are passive materials providing a signal due to the interaction of incoming gamma rays.

Scintillation detector

- Scintillation is the process by which some material, be it a solid, liquid, or gas, **emits light in response to incident ionizing radiation**.
- For example, a single crystal of sodium iodide that is doped with a small amount of thallium, NaI(Tl), coupled with a **photomultiplier** tube which converts the small flash of light into an electrical signal through the photoelectric effect.

Semiconductor detector

- In a semiconductor, there is a small energy gap between the valence band of electrons and the conduction band.
- When a semiconductor is hit with gamma-rays, the energy imparted by the gamma-ray is enough to **promote electrons to the conduction band**. This change in conductivity can be detected and a signal can be generated correspondingly.
- Germanium crystals doped with lithium, Ge(Li), and high-purity germanium (HPGe) detectors are among the most common types.

Inorganic (crystalline structure)

Up to 40000 photons per MeV
High Z
Large variety of Z and ρ
Undoped and doped
ns to μ s decay times
Expensive

E.m. calorimetry (e, γ)
Medical imaging
Fairly Rad. Hard (100 kGy/year)

Organic (plastics or liquid solutions)

Up to 10000 photons per MeV
Low Z
 $\rho \sim 1\text{gr/cm}^3$
Doped, large choice of emission wavelength
ns decay times
Relatively inexpensive

Tracking, TOF, trigger, veto counters,
sampling calorimeters.
Medium Rad. Hard (10 kGy/year)



- **Pure organic crystals:** e.x. **Anthracene and stilbene**. Both materials are fragile and it is not possible to have them in large volumes. The other feature is that the scintillation efficiency has an angular dependence from the orientation of the incoming particle compared to the crystal axis
- **Liquid organic scintillators:** obtained by dissolving organic scintillator into a liquid solvent. They have less radiation hardness than solid compounds but can be produced in large volumes => sealed. Some of them are considered flammable
- **Plastic scintillators:** the scintillator is diluted in a solvent that is subsequently polymerized (PVT Polyvinyl toluene, PS polystyrene). They are cheap and can have different volumes from fiber-like to large slabs or cubes. They are radiation sensitive. Very thin films are used for the detection of heavy charged particles (beta, ions)
- **Loaded organic scintillators:** are used to increase the Z of the material to be able to better detect gamma or neutrons (B, Li, Gd) but this reduces the light output, reducing also the energy resolution

The light output of the organic scintillator is **particle dependent**.

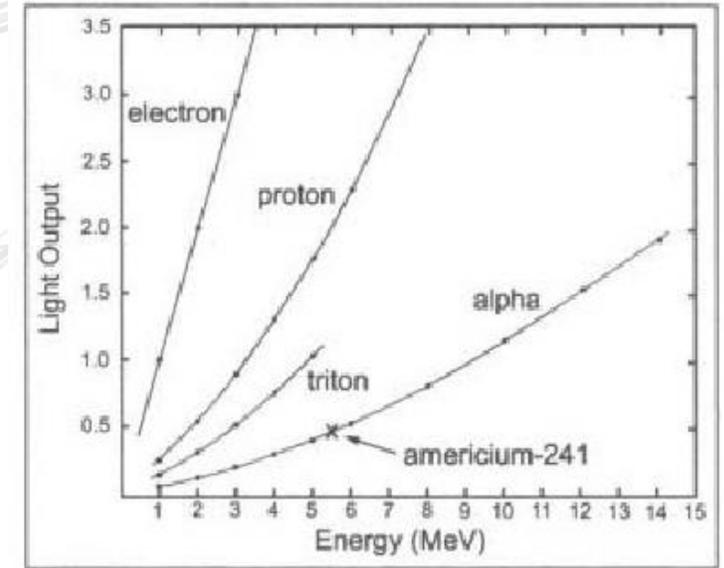
- *Particles with the same energies and different types can generate different outputs.* For heavy charged particles the light output is lower compared to electrons of the same energy
- The dependence of light output from energy deposition is usually not linear in organic scintillators. (almost linear for e-)

A high density of excited molecules along the particle track causes de-excitation without photon emission (quenching effect) → Light output becomes saturated

Light output described by Birks law:

$$\frac{dL}{dx} = \frac{S \frac{dE}{dx}}{1 + K_b \frac{dE}{dx}}$$

dE/dx Energy loss per path length
 dL/dx Light output per path length
 K_b Birks constant
 S absolute scintillation efficiency

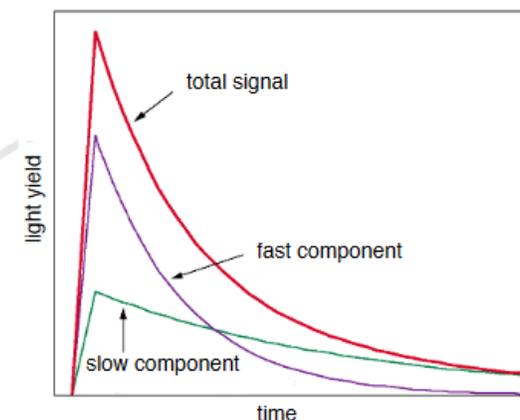


Typical values K_b $10^{-4} - 10^{-2}$ g/(cm²MeV). Empirical value determined from data

Many scintillators show a simple exponential signal decay. In case of several signal components overlap has to be considered.

- The rise time of the signal is usually very fast.
- Long component due to delayed fluorescence.

The long component is particles dependent . It is due to the interaction processes of the different particles in the material

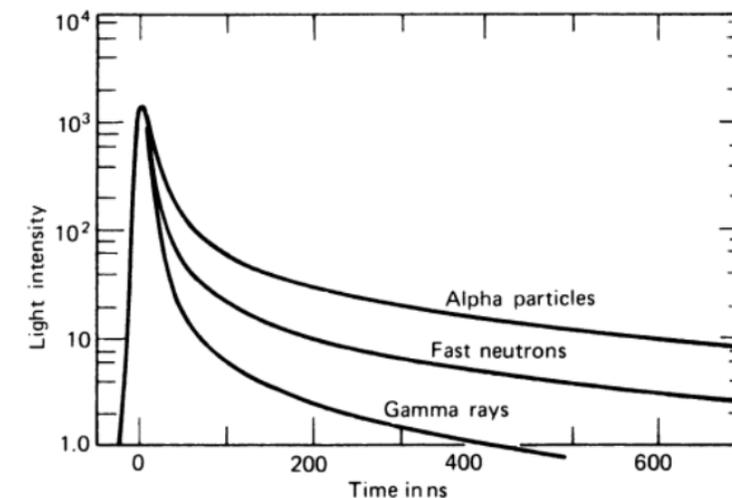


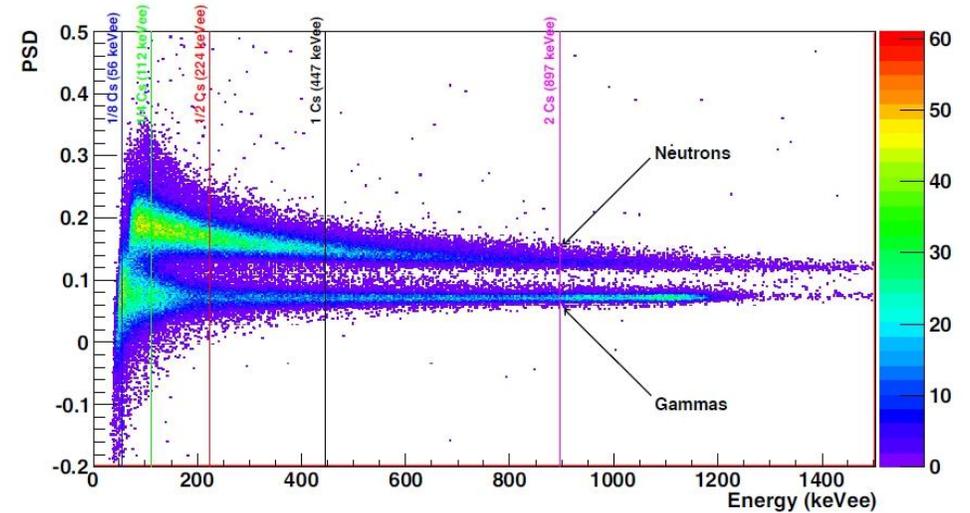
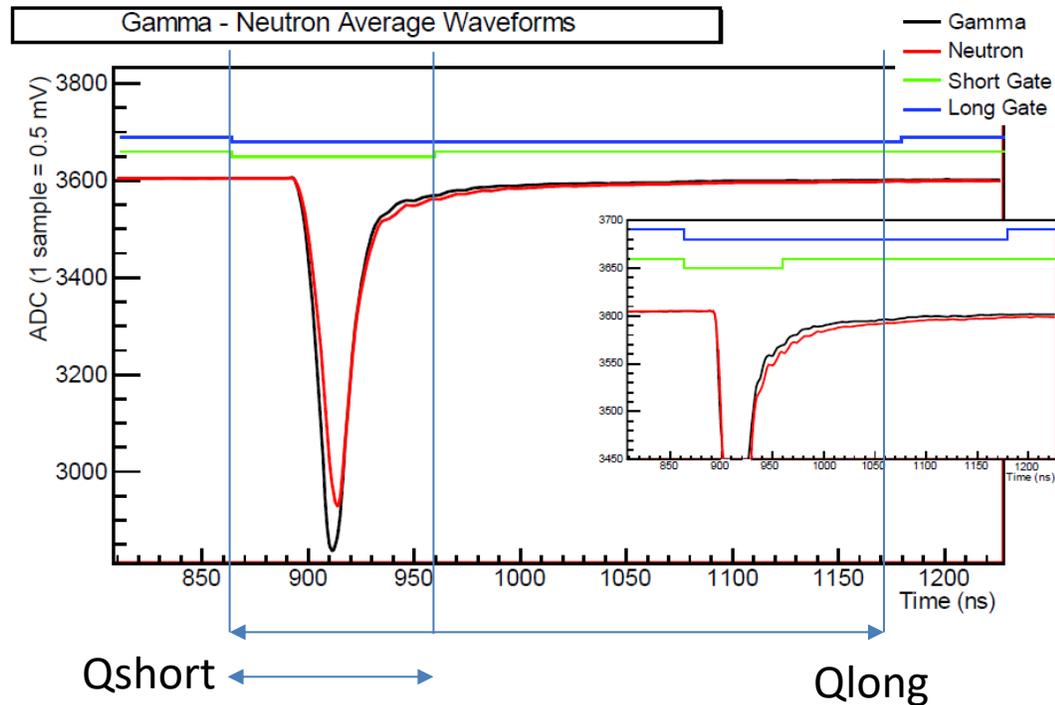
Signal vs. time of a scintillator with fast and slow component.

It is possible to distinguish different particles and their energy (spectroscopy) analyzing the signal waveform

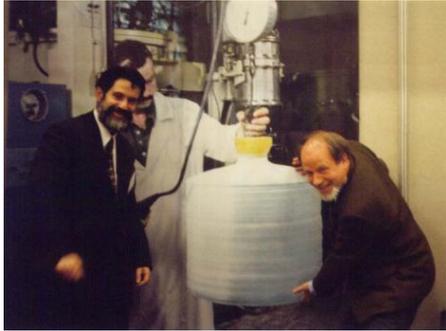


Nowadays it is possible to use a compact electronics => digitizer for an on-line PSD analysis





In the example the PSD algorithm is used to distinguish online gamma from neutron events in real time, but the same algorithm can be used to separate alpha from beta signals in other scintillators



Dr. A. Gektin and prof. C.W.E. van Eijk with a NaI:Tl ingot

The inorganic scintillators are crystals with a specific atomic structure

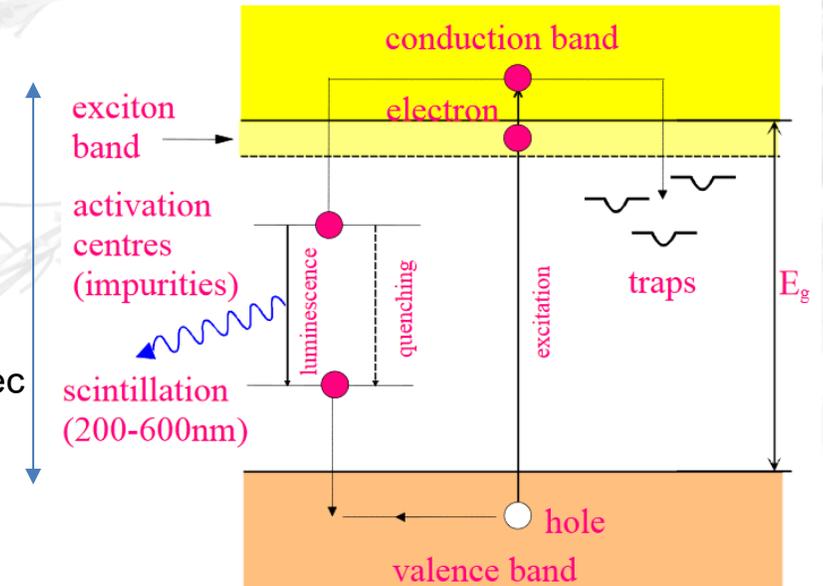
Scintillation process totally different from the organic scintillators

Doping material is used to minimize re-absorption from the crystal, since emitted light has lower energy than energy-gap.

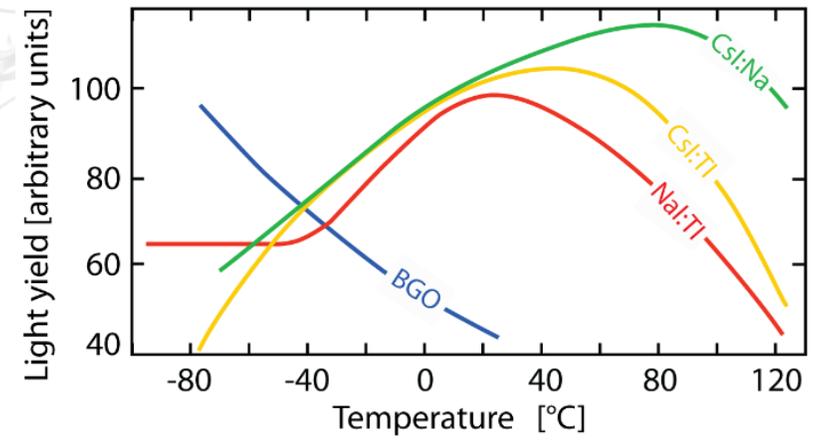
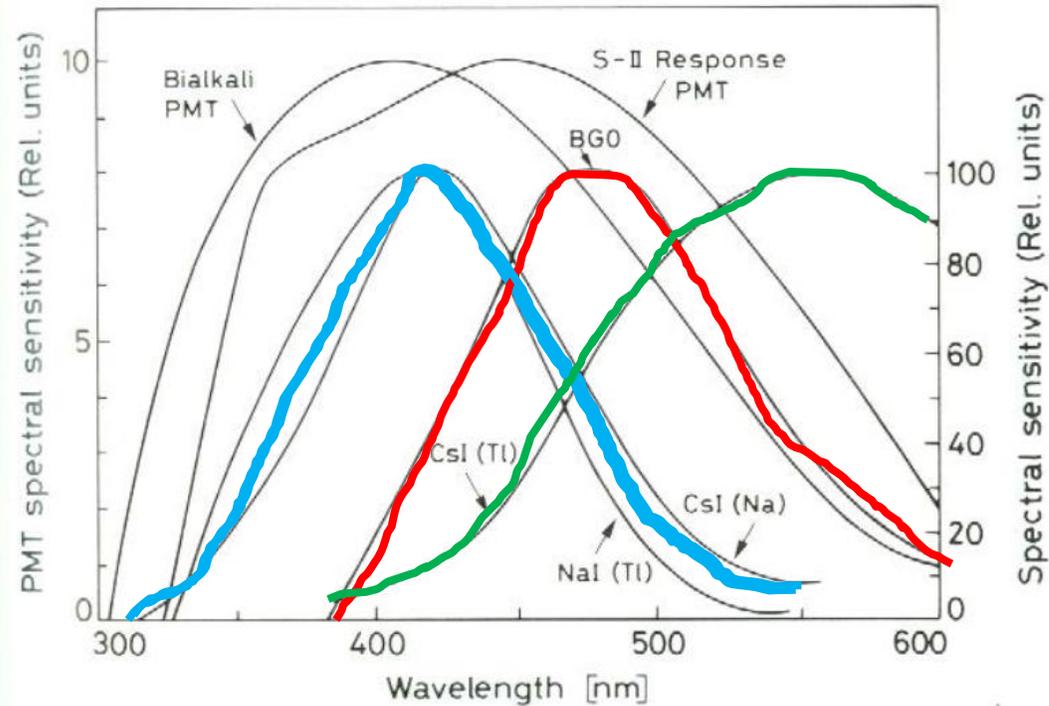
Other process in competition to scintillation:

- Phosphorescence
- Quenching
- Exciton

Example:
NaI
 $E_{\text{gap}}: 4 \text{ eV}$
 $\tau \sim 230 \text{ ns}$
Rise time
 $\Delta T \sim 10 \text{ nsec}$



High Z
High efficiency # $\gamma/\text{keV} \sim 40 \Rightarrow 4$ times better than plastic



The light emission is not monochromatic and is dopant dependent

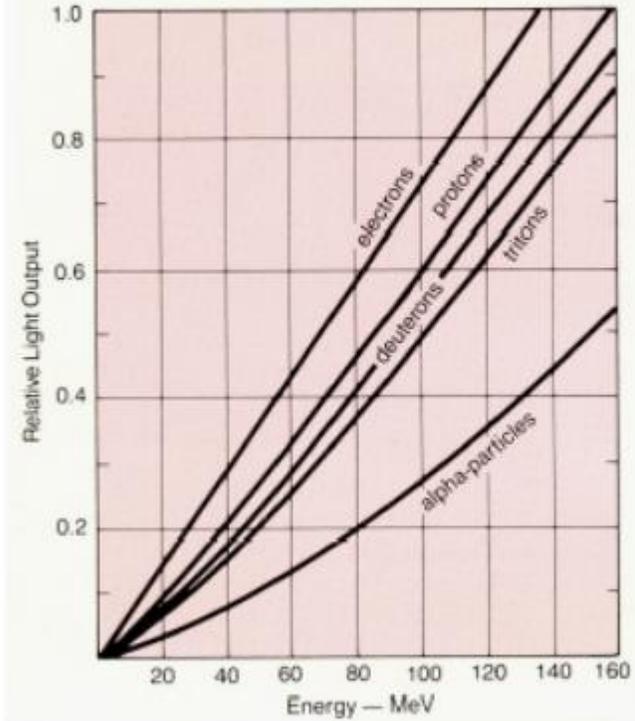
=> it is necessary to correctly associate to the correct photosensor

The temperature sensitivity depend on the e- and h+ trapping/release into the crystal structure

Opposite behavior of the organic scintillators that are almost independent of temperature in the range -60° and 20° C

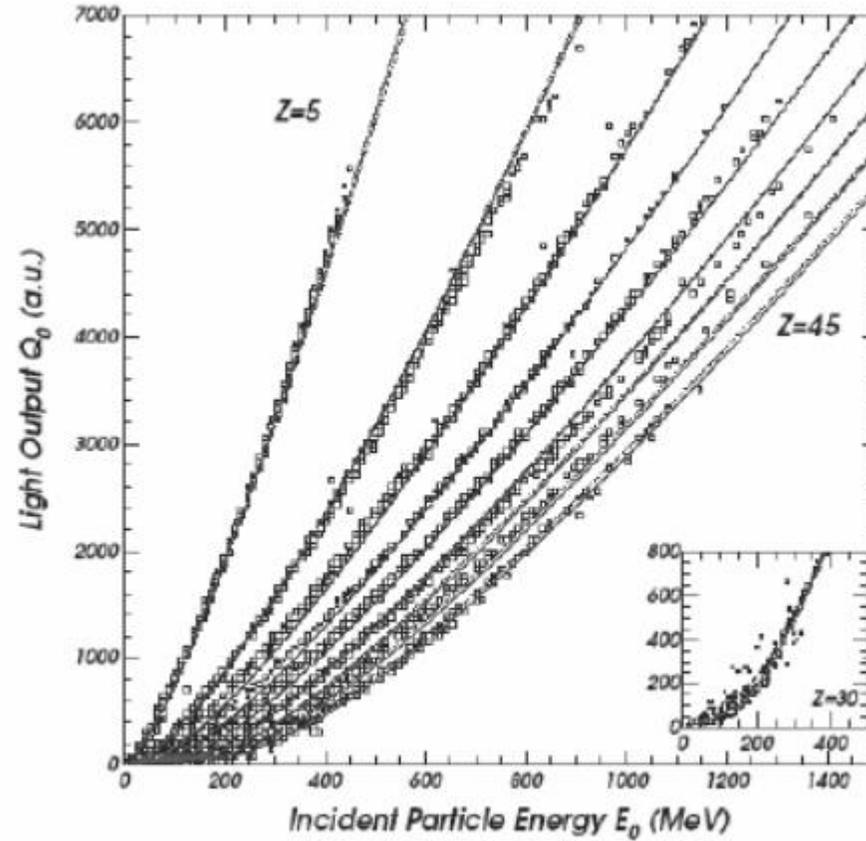
Organic Scintillator

*Bicron Premium Plastic Scintillator
Response to Atomic Particles*



Bicron Corp.

Inorganic Scintillator



INDRA Collaboration

Important inorganic crystals are:

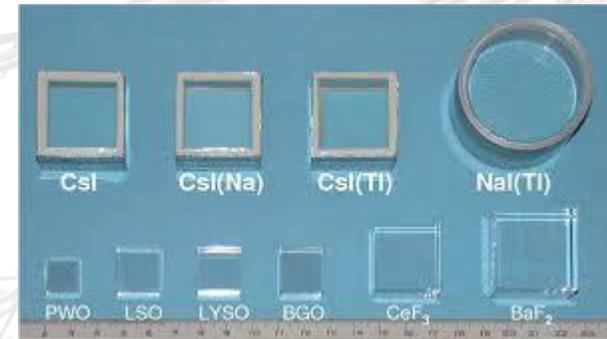
- NaI,CsI: as pure crystal or doped with Thallium ((NaI:TI),(CsI:TI))
 - BGO: $\text{Bi}_4\text{Ge}_3\text{O}_{12}$
 - GSO: Gadolinium silicate (Gd_2SiO_5), usually doped with Ce
 - BaF_2 , CeF_3 , PbWO_4
- Emitted light usuall at 400–500nm (NaI: 303nm, CsI TI : 580nm)

Advantages:

- High density
 - high stopping force
 - Extremely suitable for rays spectroscopy
- High light output $\approx 100\%$ – 400% of Anthracen
- Relative radiation resistant: especially: CeF_3 , GSO, PbWO_4 , (bad: BGO)

Disadvantages:

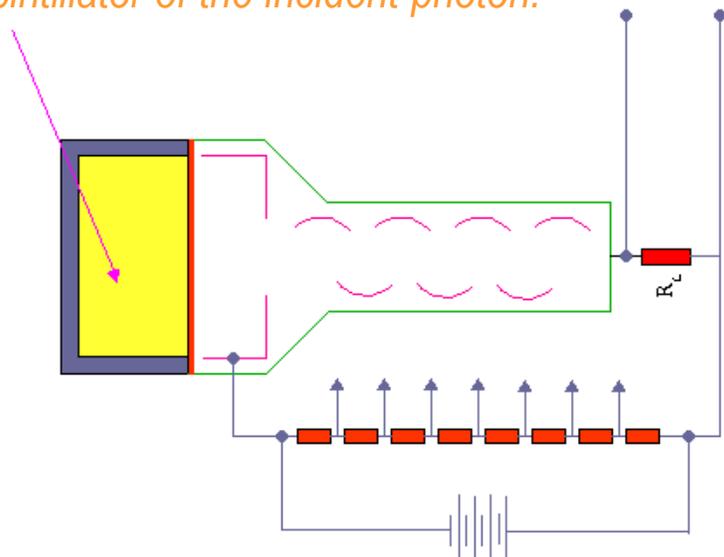
- Usually slower than organic scintillators: decay times a few hundred ns
- Some are hygroscopic: ex. NaI



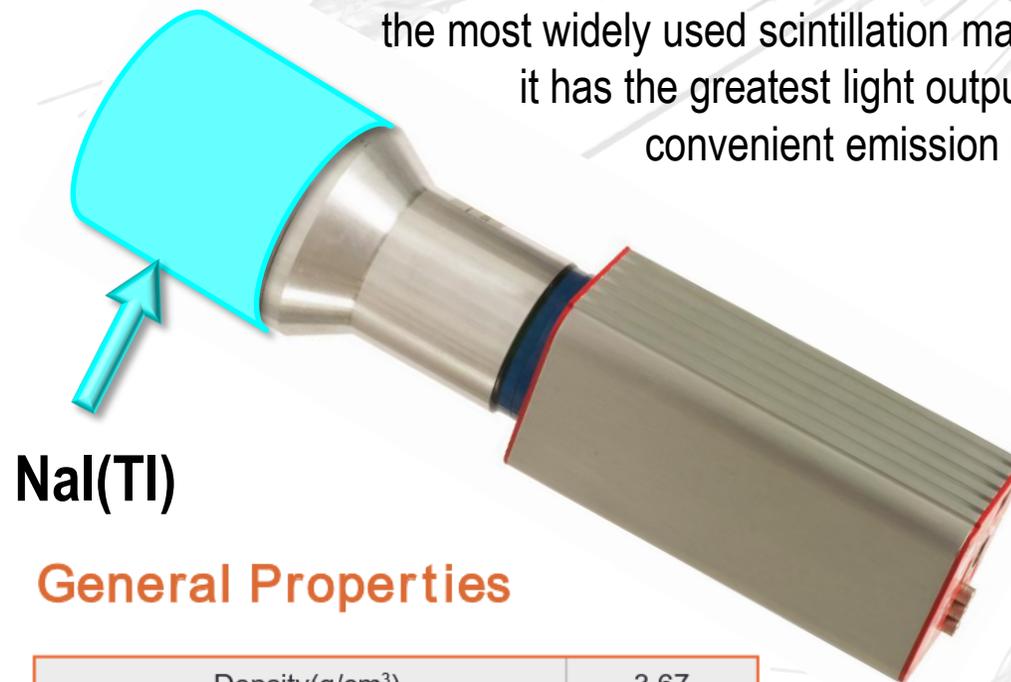
In literature the scintillator used as a reference for gamma spectroscopy is NaI

Photomultiplier Tubes (PMT) are composed of a photocathode, collection optics and multiplier section. The overall electrical signal is collected at the anode.

The intensity of the output current pulse is proportional to the energy released in the scintillator of the incident photon!



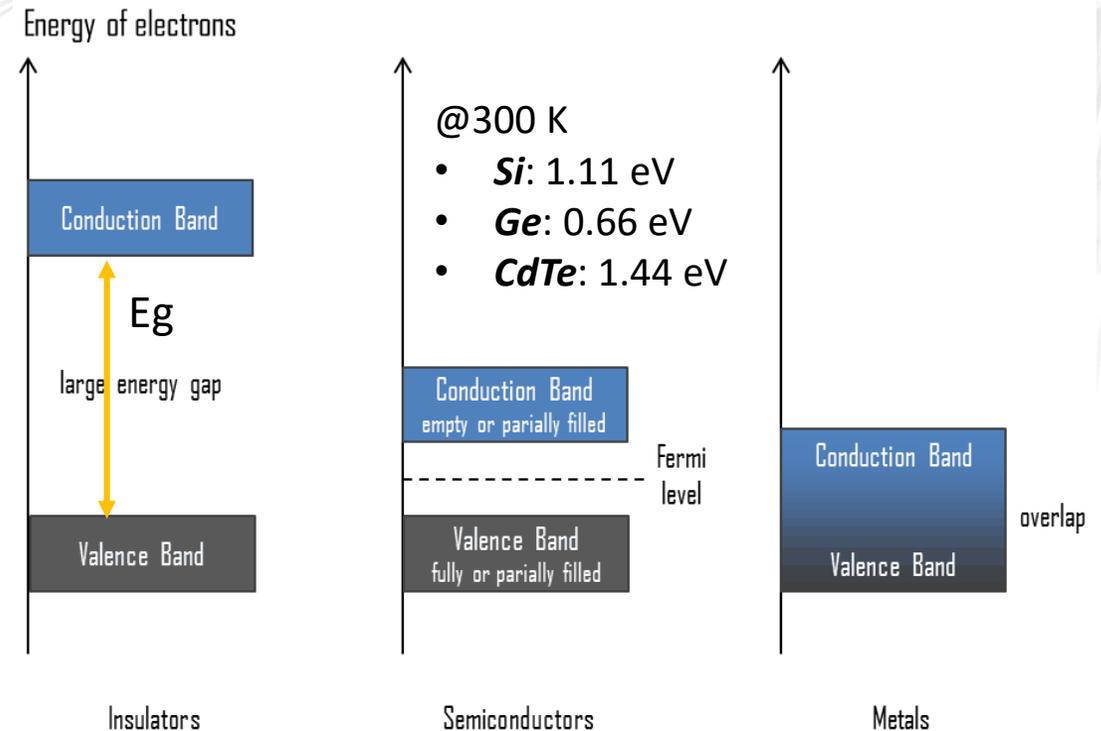
Thallium doped sodium iodide, **Nal(Tl)**, is the most widely used scintillation material, it has the greatest light output and convenient emission range



General Properties

Density(g/cm ³)	3.67
Melting point(K)	924
Wavelength of emission peak(nm)	415
Light output(Photons/Mev)	40,000
Decay time(ns)	264
Cleavage plane	(100)
Hygroscopic	Yes
Refractive index	1.85
Hardness(Mho)	2

- **Semiconductors** are inorganic or organic materials with a crystal atomic structure that have **electrical conductivity** between a metal, and an insulator.
- They have an **energy gap** of less than 4eV (about 1eV), which is the energy range between the valence band and conduction band where electron states are forbidden.
- In contrast to conductors, semiconductors' electrons must obtain **energy (e.g., from ionizing radiation)** to cross the **band gap** and reach the conduction band.
- The excitation of an electron to the conduction band creates a vacancy in the valence band. Then, an electron-hole pair is formed



The Fermi level of a semiconductor is **the highest energy level that an electron can occupy when the semiconductor is kept at absolute zero**

Thermal Excitation

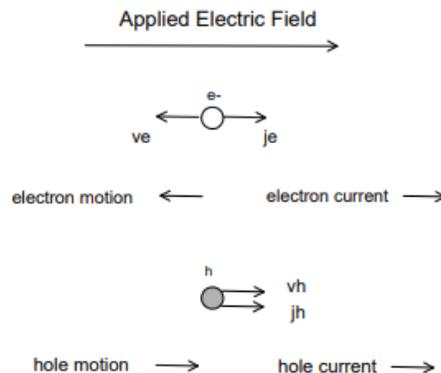
- Electron-hole pairs are also constantly generated from thermal energy without any external energy source.
- This phenomenon also occurs at room temperature.
- It is caused by impurities, structure lattice irregularities, or **dopants**.

Optical Excitation

- The energy of a single photon of the visible light spectrum is comparable with these band gaps. Photons of wavelengths 700 nm – 400 nm have energies of 1.77 eV to 3.10 eV.

Excitation by Ionizing Radiation

- Electrons may reach the conduction band when they are **excited by ionizing radiation**



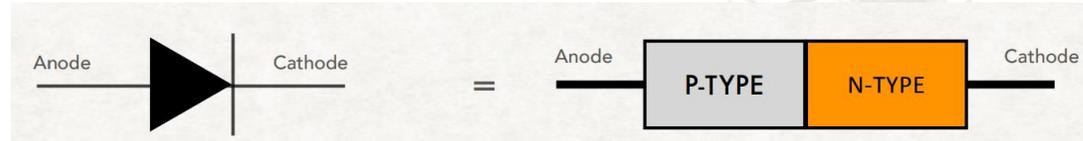
The Electric current come from e-h couples

Electric field applied:

- both the electrons and holes undergo net migration
- The electrons and holes migrate in opposite directions
- Result: net current in the same direction

Doping: These e-h couple can be obtained introducing impurities to the materials

p-n junctions are combinations of semiconductor with donor and acceptors changing the intrinsic behaviour of the device.



N-Type

- Pentavalent impurity (P, As, Sb(anthimonium), Bi)
- Donors: They have an extra e- occupy levels in the forbidden band

P-Type

- Trivalent impurity (B, Al, Ga, In)
- Acceptor: They have 1 missing e-. The acceptor energy level close to the valence band

- Free charges goes in the opposite charged region to recombine ($\sim 1V$). This motion induces an electrical field which blocks the diffusion
- **Depleted region:** At the equilibrium creation of an empty zone where the majority charge carriers are neutralized
- **Reverse biased operation:** blocks current flow. (N impurity concentration on the initial semiconductor material)
Increasing the bias increases the depleted region depth
- When a gamma ray arrive in the depleted region it interact with the material producing e-h pairs
- If E is the radiation energy and w the energy required to produce an e-h pair $\Rightarrow E/w$ number of e-h pairs produced
- The electric field applied induce motion of the e-h pairs that, once collected, generate an electrical signal proportional to E

Energy resolution: # of information carriers:

Scintillator:	> 100 eV / photon
Gas:	20 – 40 eV / charge
Silicon:	3.6 eV / charge
Germanium:	2.8 eV / charge

Silicon advantages:

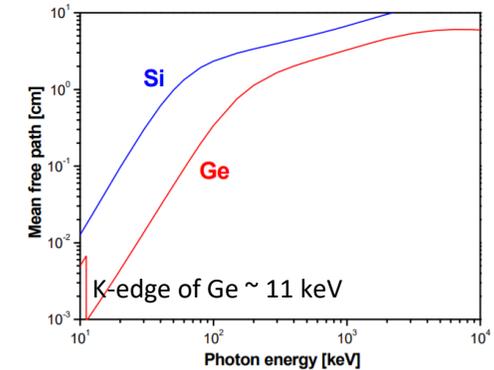
- low ionization energy (good signal)
- long mean free path (good charge collection efficiency)
- high mobility (fast charge collection)
- low Z (low multiple scattering)
- production technologies very well developed

Germanium: higher Z → detect γ radiation (needs cooling...)

- High leakage current => HPGe need cooling while Si can work at room temperature

@300 K

- **Si:** 1.11 eV
- **Ge:** 0.66 eV
- **CdTe:** 1.44 eV

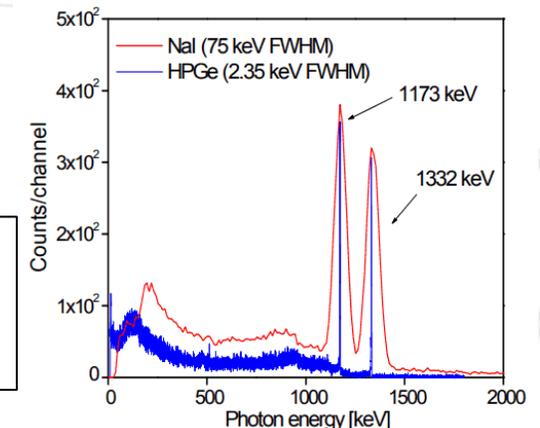


- Depletion depth of Si of about 1 mm => Good for alpha and beta particle or low energy gamma ray
- Photons requires larger volumes detector => HPGe => Depletion depth of several centimeters
- Very high number of charge produced => Better energy resolution

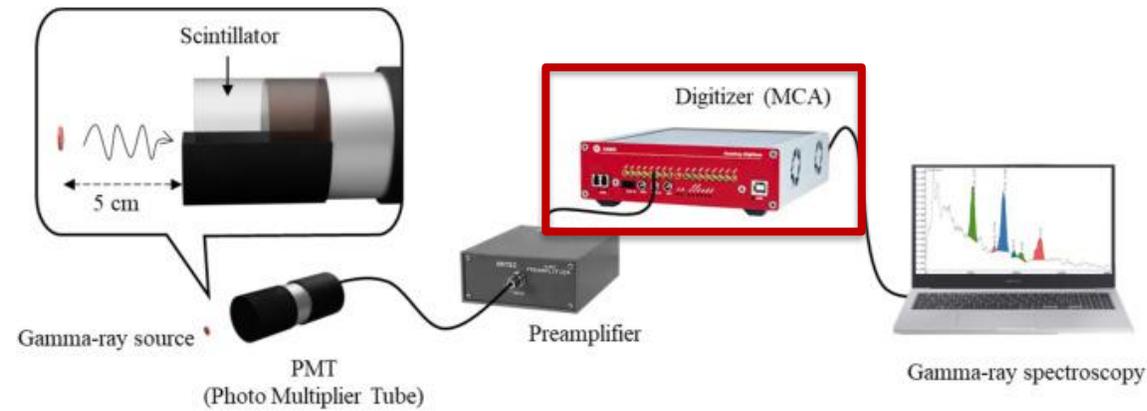
Energy resolution @1.3 MeV:

- 8% for NaI
- 0.15% HPGe

If the application foresees the ID or quantification of a sample with unknown radionuclides, better is the E resolution and better is the ID and its quantification

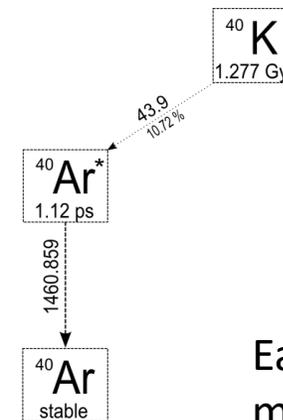
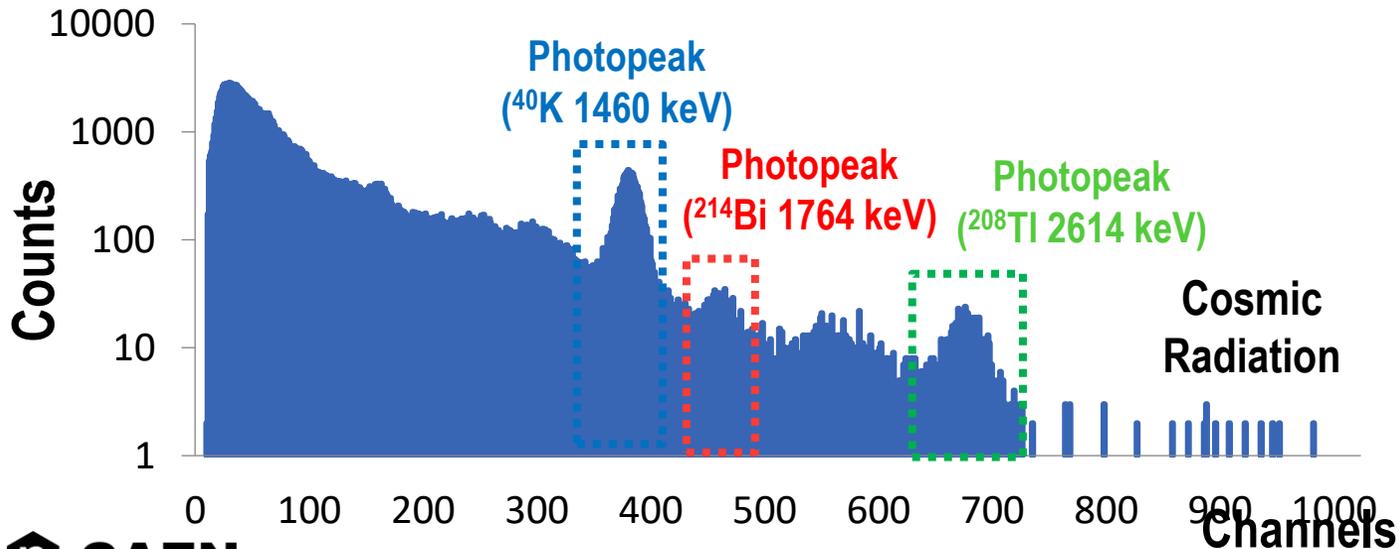


- The basic components are:
 - **DETECTOR**, which collects the energy deposition of the incoming radiation and produces a voltage signal proportional to the energy
 - **ANALOG-TO-DIGITAL CONVERTER (ADC)**, to convert voltage signal into a digital number
 - **MULTI-CHANNEL ANALYZER (MCA)**, to bin the numbers into the spectrum
 - **COMPUTER**, to compare spectra of known isotopes and try to identify radioactive material
- Additional components may include signal amplifiers, rate meters, peak position stabilizers, and data handling devices.
- Currently the acquisition can be managed by a single electronic device which simplifies the acquisition chain.



- A gamma spectrum is the spectrum acquired where each bin contain the number of event with that energy.
- The photopeak characterize the gamma spectrum
- The photopeak is made of photons releasing all their energy into detector (photoelectric effect)
- Being able to correctly identify the energy of the gamma peak, we are able to identify the presence of radionuclides

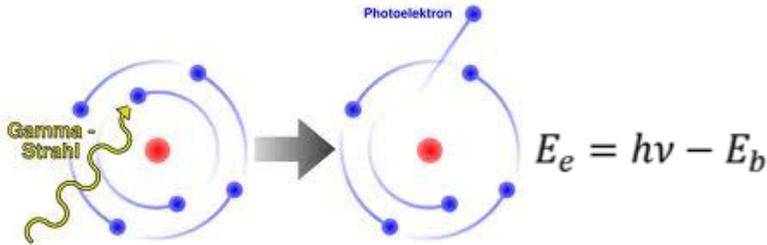
- The electronics that can be used is a MultiChannel Analyzer (MCA) able to classify input pulses base on their height or shape saving them in a memory and are associated to an ADC. The output of every channel can be visualized in a pulse amplitude spectra.
- An Analog-to-Digital Converter (ADC) generates a digital signal proportional to the amplitude of an input pulse. The ADC can be used combined to an MCA to generate energy distributions of radioactive samples.



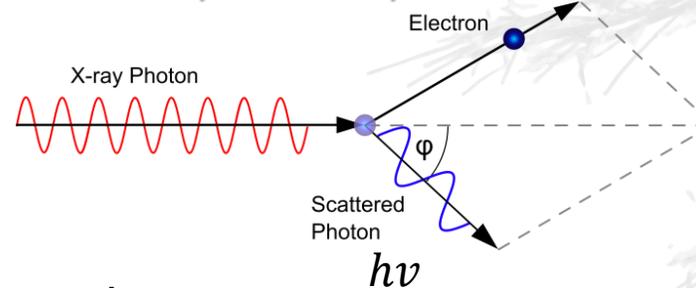
Ex. Monochromatic photons beam

Each radioisotope has its own monochromatic gamma emission(s)

Photoelectric effect [$\gamma + \text{atom} \rightarrow \text{ion} + e^-$]

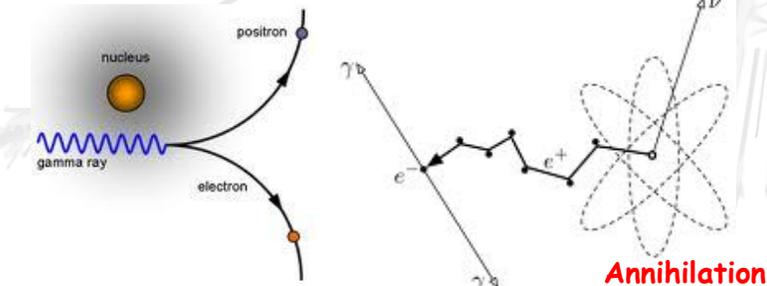


Compton effect [$\gamma + e^- \rightarrow \gamma' + e'^-$]



$$E'_\nu = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2}(1 - \cos\theta)}$$

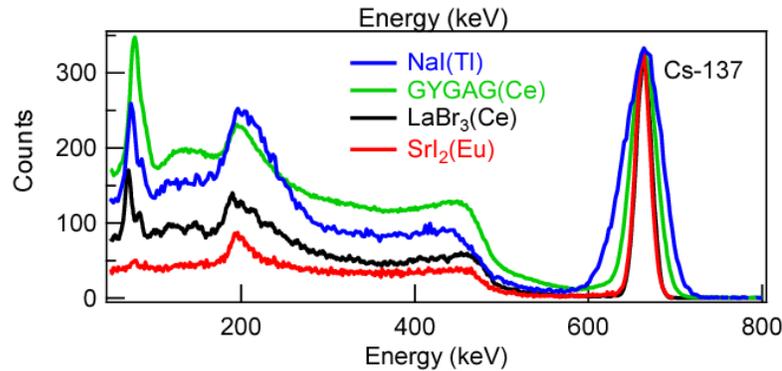
Pair production [$\gamma + \text{nucleus} \rightarrow e^+ + e^- + \text{nucleus}$]



- Photon interacts ONLY with atomic electrons, No with a free electron
- Most probable electron from the outer electronic shells
- In the interaction, creation of an electron-ion couple. The hole is immediately filled with free electron capture or reorganization of the electronic structure => Following emission of x-rays or Auger electrons
- Typical effect of the low energy region in the ~ keV region

- Photon interacts atomic electrons of the absorber material
- The interacted photon is scattered with a certain angle (θ) and the energy transferred allows the electron emission from the atom
- All the emission angles are allowed, but the scattered angle is energy dependent => Klein-Nishina Formula
- Typical interaction of radioisotope energy, hundreds of keV region

- Threshold effect => The pair production is possible only if the energy of the photon is larger than twice the energy at rest of the electron
- It is possible only in the Coulombian field of the nucleus
- The photon disappear for appearing a couple made of electron and positron
- The energy in above the threshold energy goes into kinetic energy of the couple
- The positron is annihilated rapidly with the following emission of 2 photons
- Typical interaction in the several MeV region

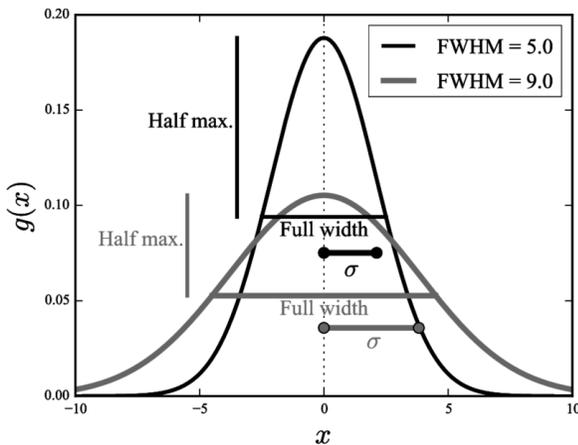


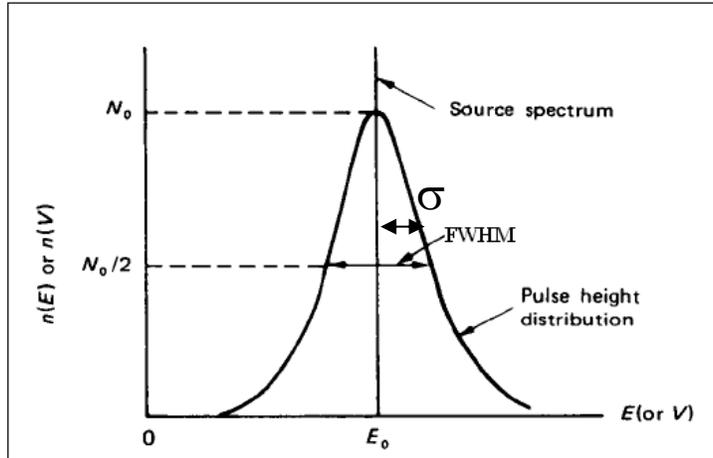
From the comparison of different energy spectra the energy distribution of the events, for the same source (^{137}Cs) is different.
Some are larger than others.

If the events distribution of a gaussian function, for the same statistics we can observe different width for the same detector.

The width is due to fluctuations of the measurement. Mainly 3 components:

1. Statistical noise induced by the discrete nature of the measurement (most important contribution, is the one determining the resolution)
2. Noise induced by the system, mainly due to the electronics or the photosensors
3. Drift of the detector characteristics along the measurement period





A peak from a scintillator can be describe using a Gaussian distribution:

- of Energy (E_0), the most probable value
- σ the standard deviation
- FWHM full width half maximum

The energy resolution of a photopeak is defines as:

$$R = \frac{FWHM}{E_0} \quad \text{Is usually expressed in \%}$$

If we consider:

- N the number of photoelectrons produced following the Poisson distribution
- Scintillator response linear as a function of the energy released

We can express the Energy resolution as:

$$R = \frac{FWHM}{E_0} = \frac{2.35 \sqrt{N}}{N} = \frac{2.35 \sqrt{CE}}{CE} = \frac{K}{\sqrt{E}}$$

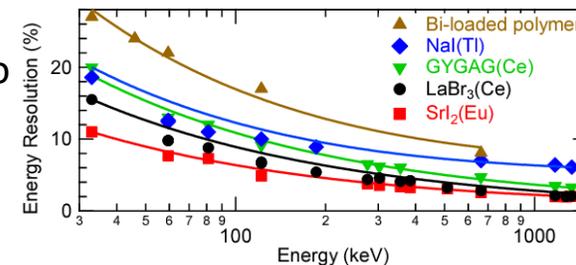
$$FWHM = 2.35 \sigma$$

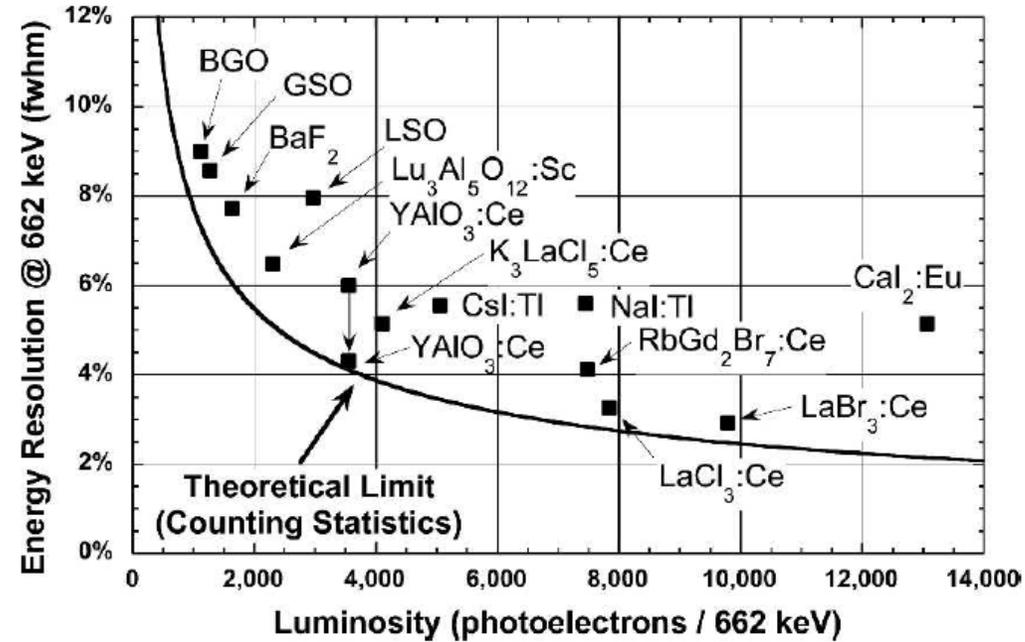
$$\sigma = \sqrt{N}$$

$$E_0 = N$$

C;K Constants

BUT, scintillators do not have a linear energy response

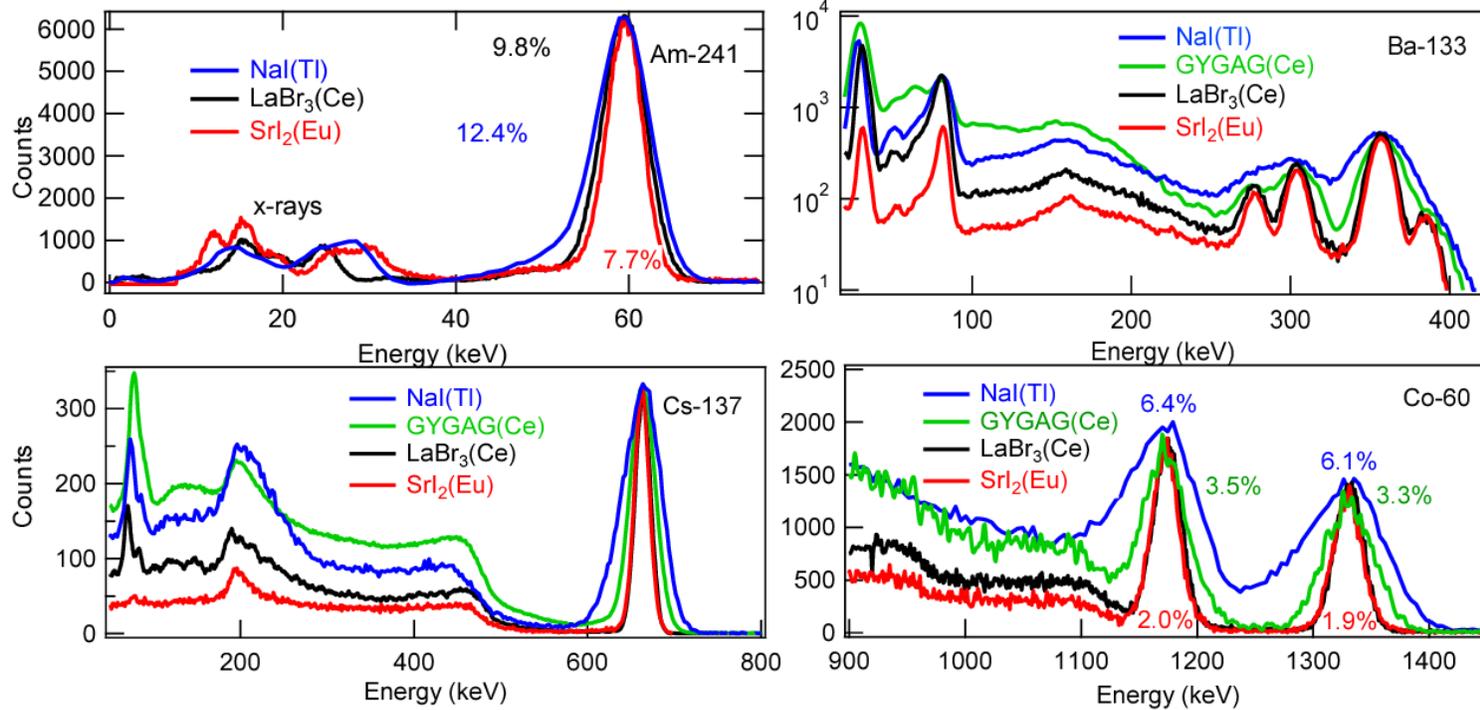




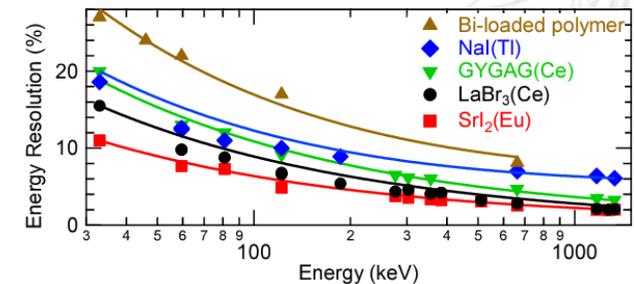
Radiation detector materials: An overview

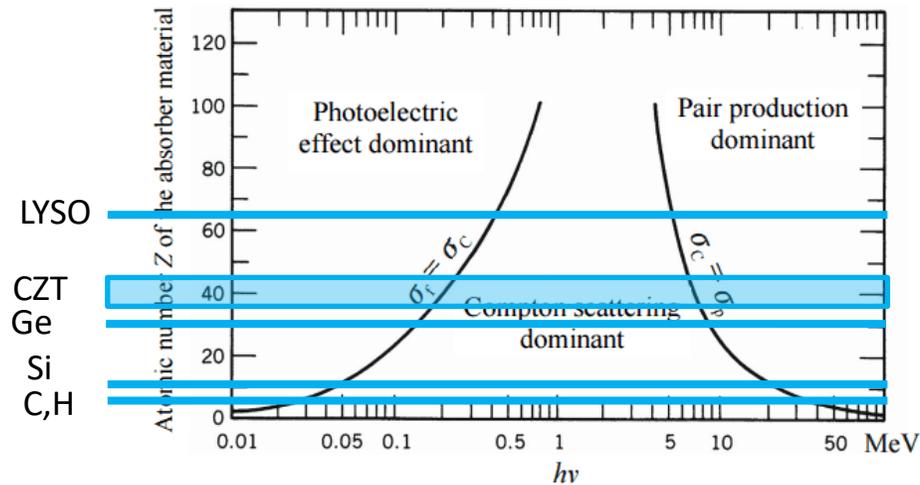
DOI: 10.1557/JMR.2008.0319

	Density (g/cm ³)	Maximum emission wave length (nm)	Decay time (μs)	Light yield (photons/gamma MeV)	Refractive index
NE102A (plastic)	1.03	423	0.002	10000	1.58
NaI(Tl)	3.67	415	0.23	38000	1.85
CsI(Tl) (slow/fast)	4.51	540	3.34/0.68	65000	1.8
BGO	7.13	480	0.3	8200	2.15
BaF ₂ (slow/fast)	4.89	310/220	0.63/0.00006	9500/1400	1.56
PbWO ₄	8.28	420	0.01	400	2.2
YAP(Ce)	5.37	370	0.027	18000	1.95
LaBr ₃ (Ce)	5.29	380	0.026	63000	1.9



N. J. Cherepy *et al.*, "Comparative gamma spectroscopy with SrI₂(Eu), GYGAG(Ce) and Bi-loaded plastic scintillators," *IEEE Nuclear Science Symposium & Medical Imaging Conference*, Knoxville, TN, 2010, pp. 1288-1291.
doi: 10.1109/NSSMIC.2010.5873975





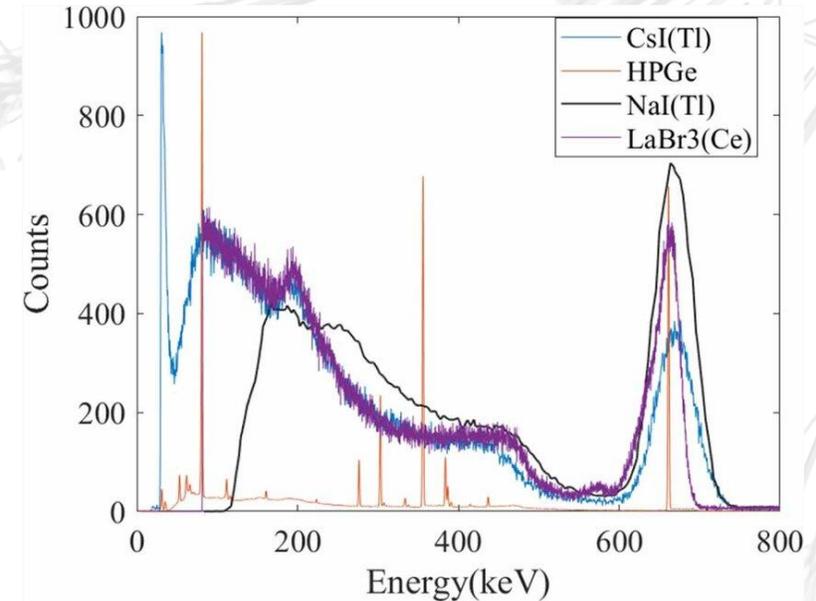
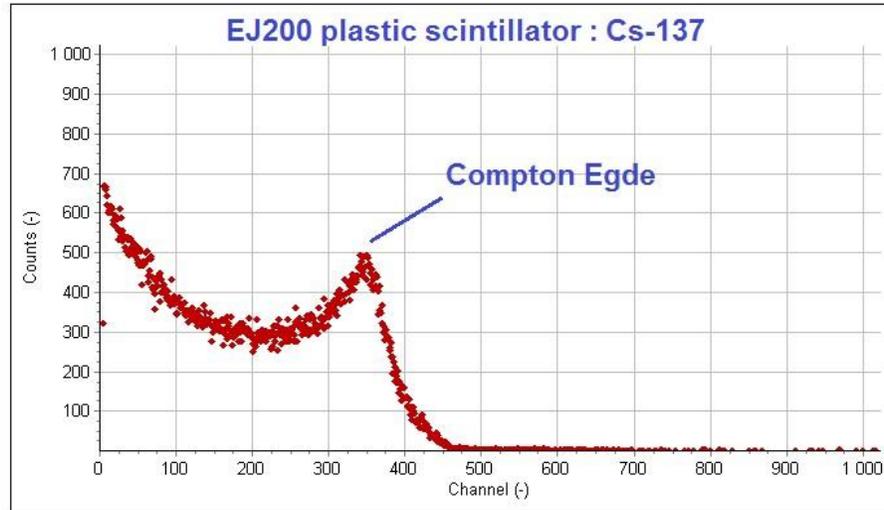
Relative importance of the 3 processes described as a function of the incoming photon energy and dependence from the atomic number of the absorber material

The solid lines represent the equal probability between:

- Photoelectric effect and Compton effect (low energy)
- Compton effect and Pair production (high energy)

- Photoelectric effect => Low energies => Below 1 MeV
- Compton => Medium energy => Few MeV
- Pair Production => Above few MeV

Energy spectra with ^{137}Cs (@662 keV)



Organic scintillator:

- Very low Z
- Low density
- PSD capability for some of them
- Poor energy resolution
- Poor detection efficiencies
- Very fast signal
- Low cost
- Up to large size dimensions
- Applications: TOF, alpha beta and gamma detection, counting system, veto
- No gamma spectroscopy or spectrometry

Inorganic scintillator:

- High Z
- High density
- Good energy resolution
- Good detection efficiencies
- Wide range of costs
- Crystal growth dependent on compounds
- Applications: gamma spectroscopy and spectrometry (of specific elements)
-

Semiconductor:

- Very high Z
- Very high density
- Optimal energy resolution
- Strong dependence of detection efficiency (crystal dimensions)
- Wide range of costs
- If HPGe cooling needed
- Applications: Gamma spectroscopy and spectrometry

Thank you for your attention!

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