

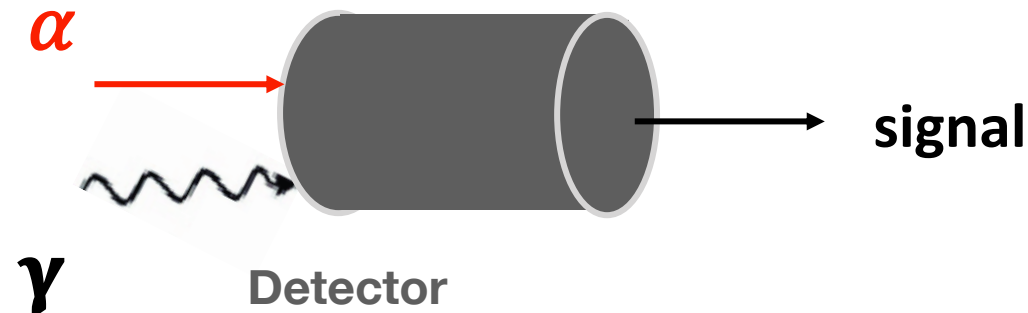
Lecture: General characteristics of detectors

Chapter 5 in Leo:

5 except 5.7.1

Chapter 4 in Knoll

Detection



- Radiation enters the detector and interacts with its active volume.

Through different processes depending on the type of radiation as we discussed in the previous lectures.

- A charge, Q , is created as a result of interaction with the detector material

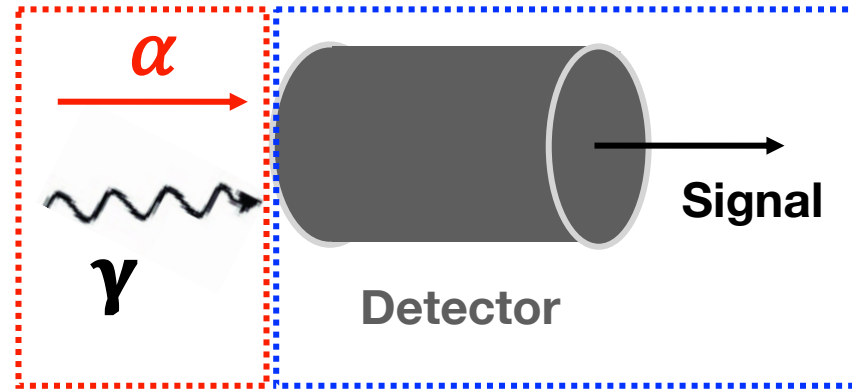
Charge creation is essentially instantaneous (typically within a few ns in gases and a few ps in semiconductors)

- The created charge must be collected and converted into a form of an electrical signal

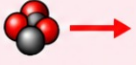
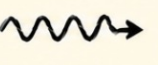
Charge collection time, t_c , is the time required to fully collect the charge (=charge carriers). t_c is around few milliseconds in ionization chambers and few nanoseconds in semiconductor diode detectors.

- Charge creation is extremely fast. Therefore, in many detectors, the charge collection process determines the detector response time. Very important.

Each detector material reacts **differently**

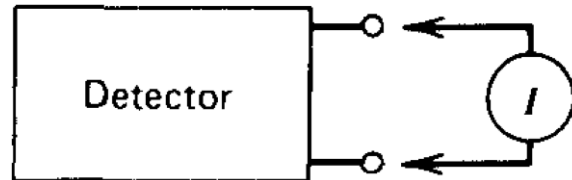


Particles interact **differently**

Radiation type	Detector type	Charge carriers / secondary product produced
α 	Gaseous detectors (e.g. ionization chamber, proportional counter, GM)	Electron-ion pairs (electrons and positive ions)
β 	Gaseous or semiconductor detectors (e.g. gas detectors, Si detectors)	Electron-ion pairs (gas) or electron-hole pairs (semiconductor)
γ 	Scintillation detectors (e.g. NaI(Tl), BGO)	Scintillation photons (produced by secondary electrons via ionization and excitation)
γ 	Semiconductor detectors (e.g. high-purity Ge detectors)	Electron-hole pairs (electrons and holes)
n 	Detectors with converter materials (e.g. ^3He , ^{10}B , ^6Li , or hydrogen-rich scintillators)	Electron-ion pairs (gas) or scintillation photons (after nuclear reactions producing charged particles)

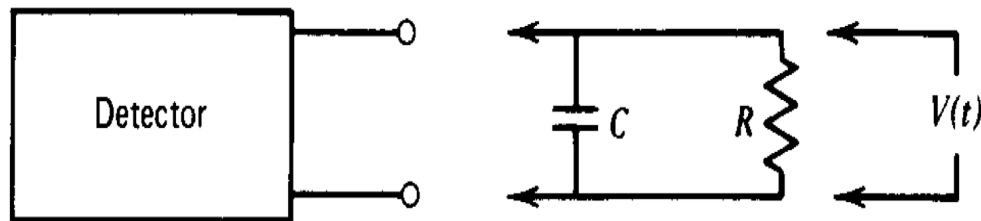
Different radiations interact differently with detector materials and produce different charge carriers or secondary products, which are then collected and converted into an electrical signal (current or voltage pulse).

Current mode



- Connect the detector output to a current measuring device such as an ammeter.
- Event rates are very high
- Used for radiation dosimetry

Pulse mode (Voltage pulse)



RC circuit

$$V = \frac{Q}{C}$$

- Event rates are not very high
- Used for radiation spectroscopy where the amplitude and time information is preserved.

$$Q \propto V \propto E$$

Today

- Sensitivity
- Detector Response
- Pulse height spectra (Response function in Leo)
- Detector response time (self study)
- **Energy resolution**
- **Detector efficiency**
- **Dead time**

Sensitivity

“Capability of producing a usable signal for a given type of radiation and energy”

“No detector can be sensitive to all types of radiation at all energies”

Sensitivity depends on:

- **Cross section for ionization**
- **Detector mass and volume**
- **Detector noise**
- **Absorber**

Detector response

$$Q \propto V \propto E$$

- Most of the time the detector *response to a given radiation is linear so that* the spectrum of pulse heights measured from the detector corresponds directly to the energy spectrum of the incident radiation.

- While a given detector, linear for one type of radiation, can be **non-linear** for another type.

Example:

Detection of **heavy charged particles (such as protons, deuterons) in organic scintillators** is non-linear.

While the response of organic scintillators to electrons is linear.

Pulse height spectra

1. More deposited energy $\rightarrow$ larger pulse.

Example:

100 keV (E_1) $\rightarrow$ 0.5 V (H_1)

200 keV (E_2) $\rightarrow$ 1 V (H_2)

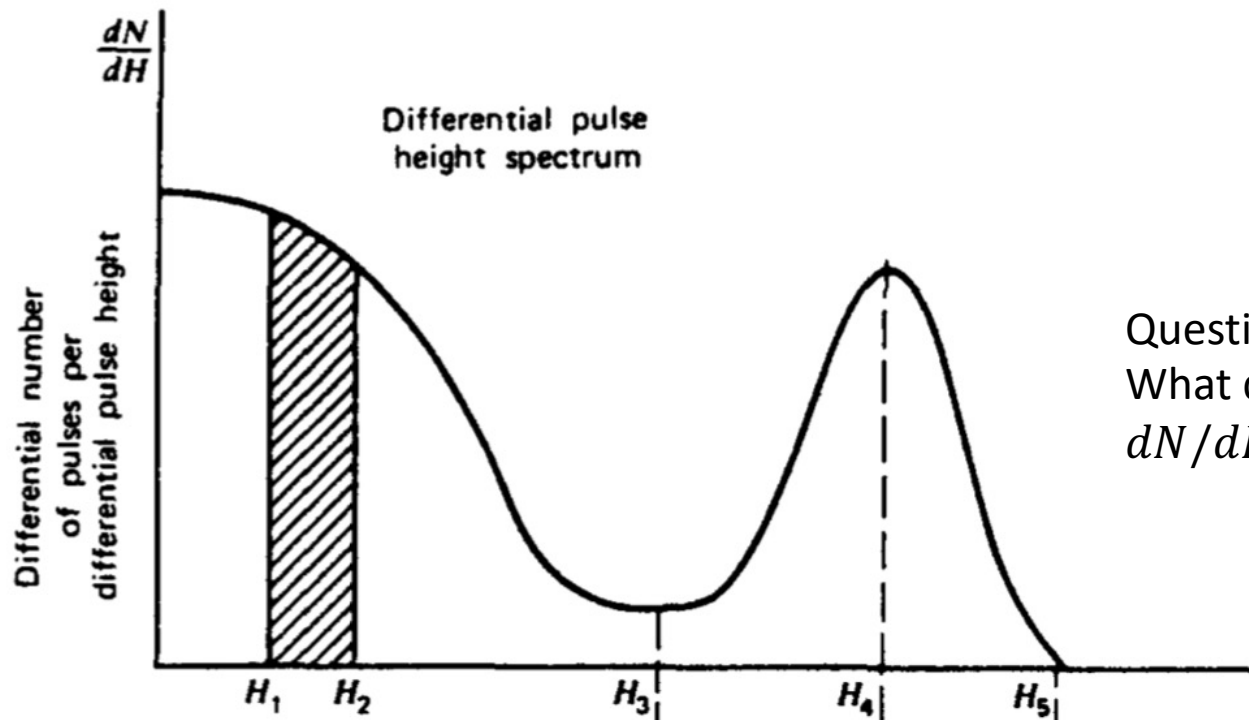
1000 keV (E_4) $\rightarrow$ 5 V (H_4)

2. Thousands of interactions produce thousands of pulses.

3. Count how many pulses have each pulse height.

$\rightarrow$ pulse-height spectrum

Number of pulses per increment
of pulse height (dN/dH)



Question:

What does the integral of dN/dH between H_1 and H_2 represent?

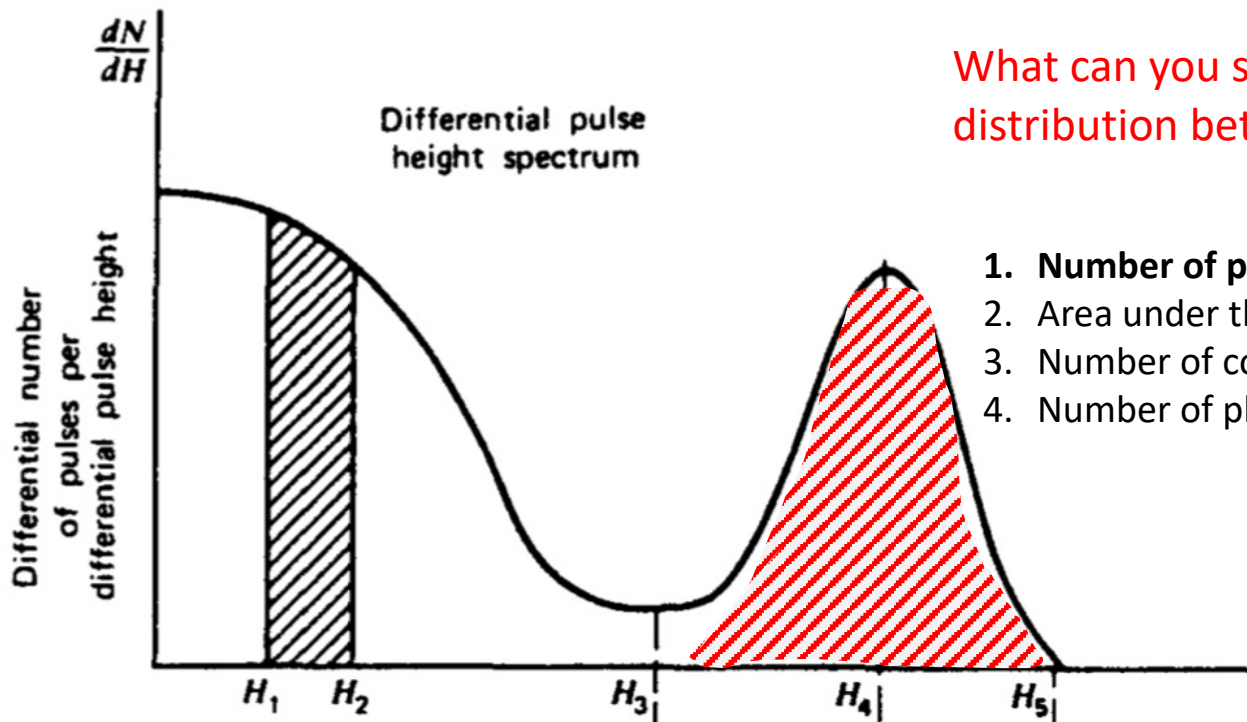
Pulse height (H) $\propto$ Deposited energy (E)

Pulse height spectra

$$\text{number of pulses with amplitude between } H_1 \text{ and } H_2 = \int_{H_1}^{H_2} \frac{dN}{dH} dH$$

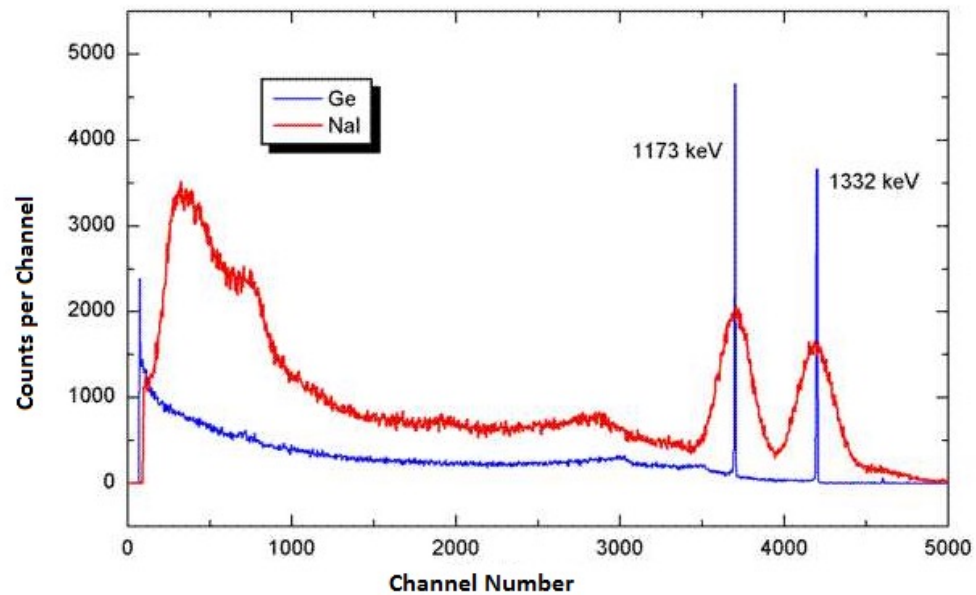
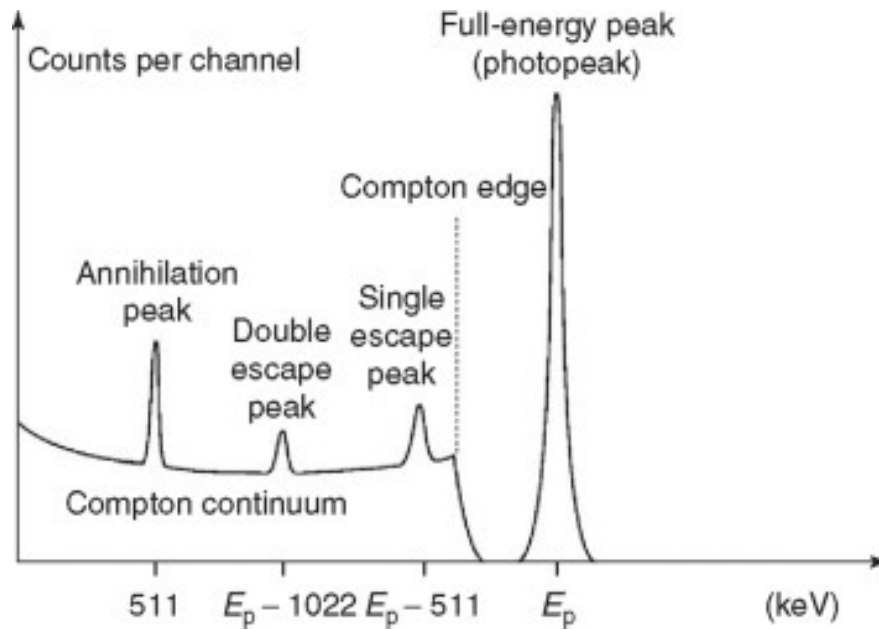
Number of pulses per increment
of pulse height (dN/dH)

What can you say about the integral of the dN/dH distribution between H_3 and H_5 ?



1. Number of pulses with pulse heights between H_3 and H_5
2. Area under the peak
3. Number of counts between channels H_3 and H_5
4. Number of photons between energies E_3 and E_5

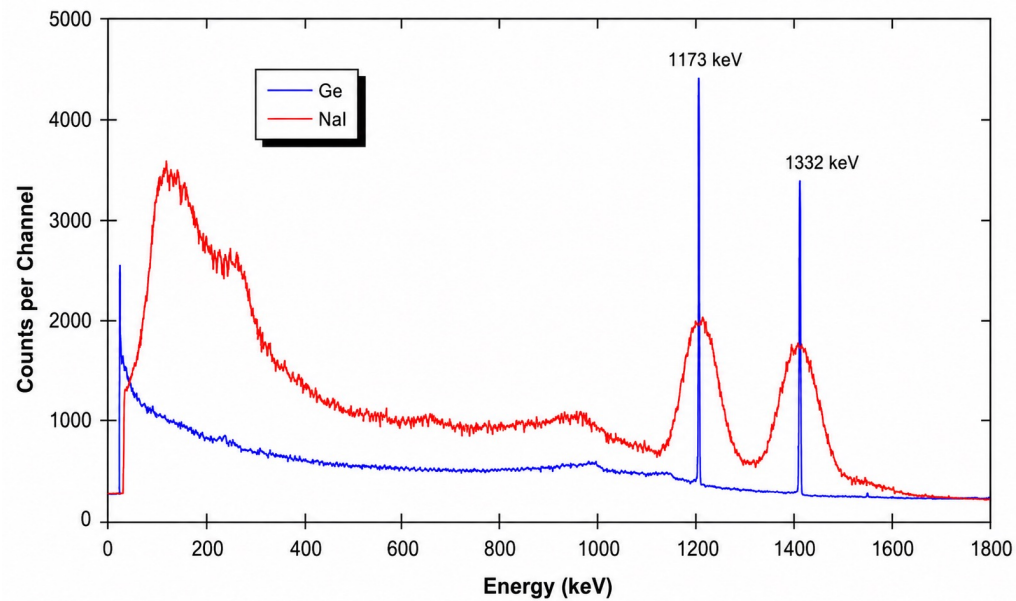
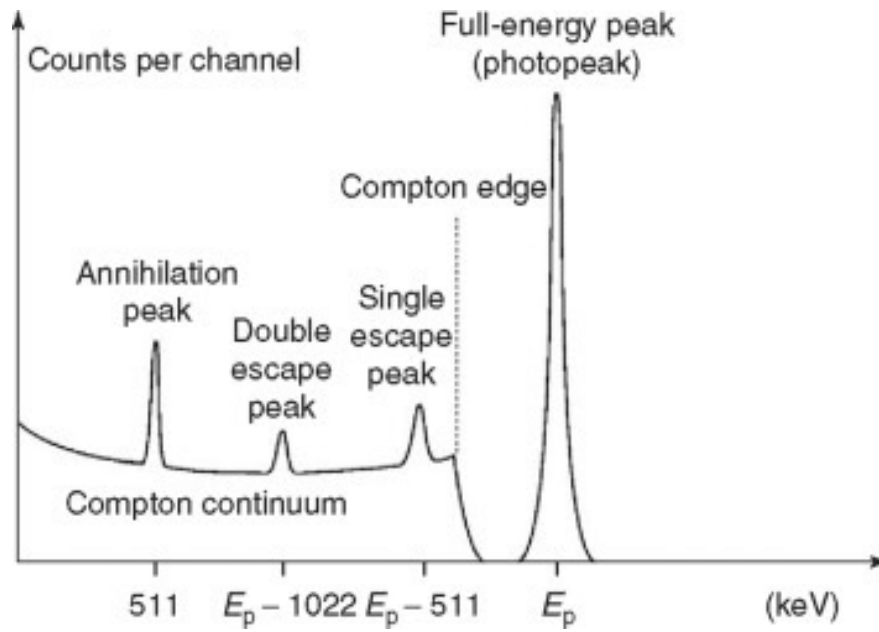
Pulse height (H) $\propto$ Deposited energy (E)



Pulse height spectrum



Energy spectrum



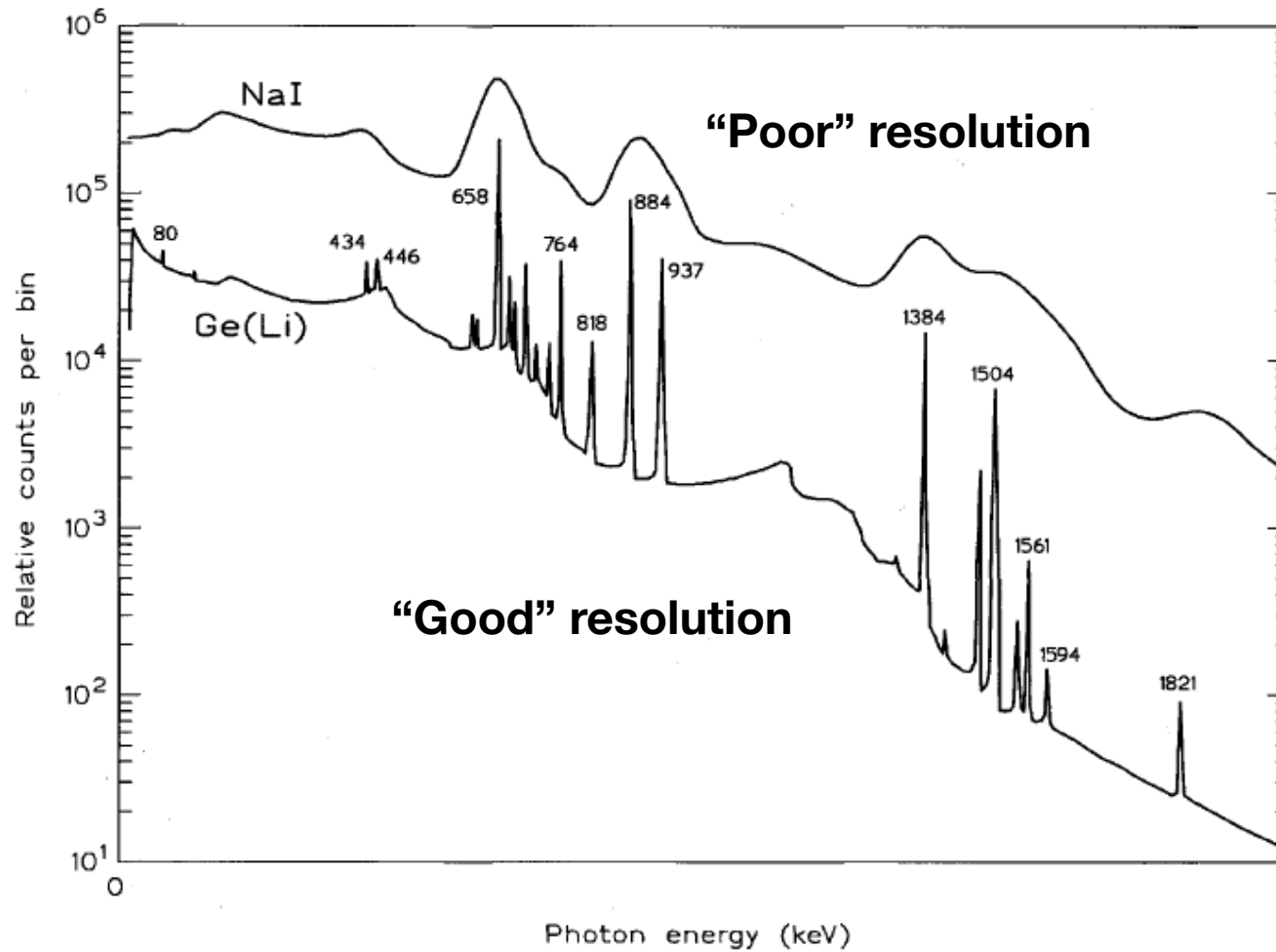
Pulse height spectrum



Energy spectrum

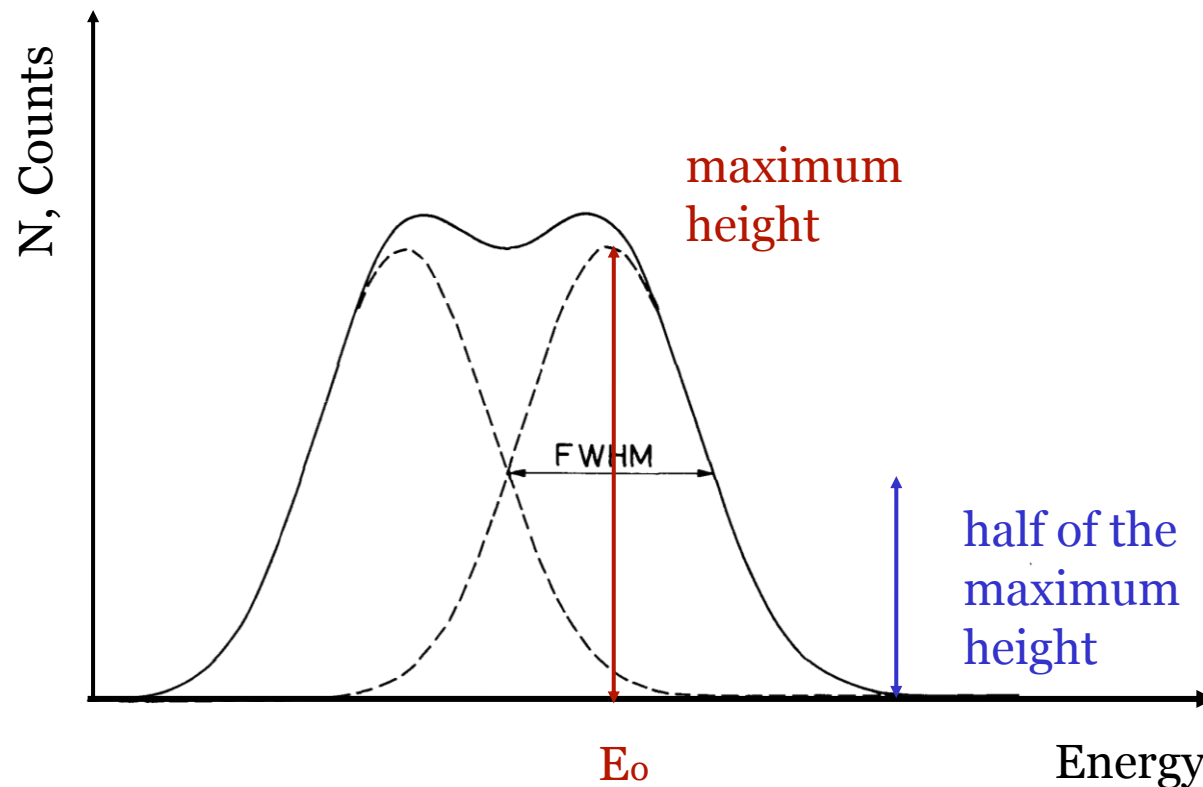
Energy resolution

For determining the energy of any incoming radiation, energy resolution becomes very important. It is the most important property when it comes to “radiation spectroscopy”



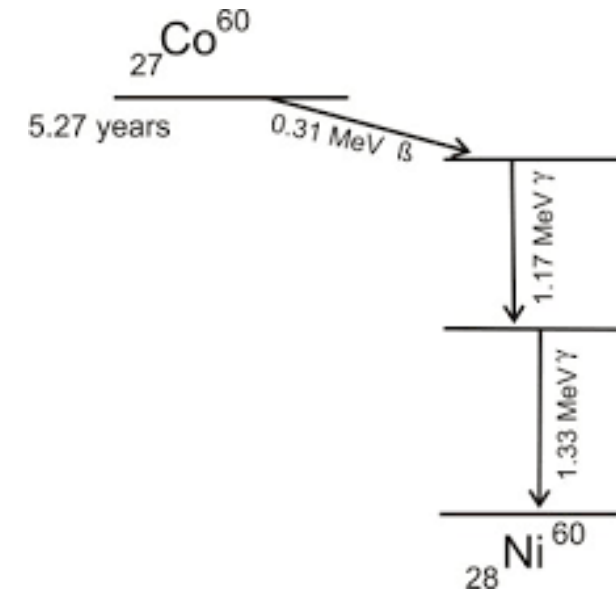
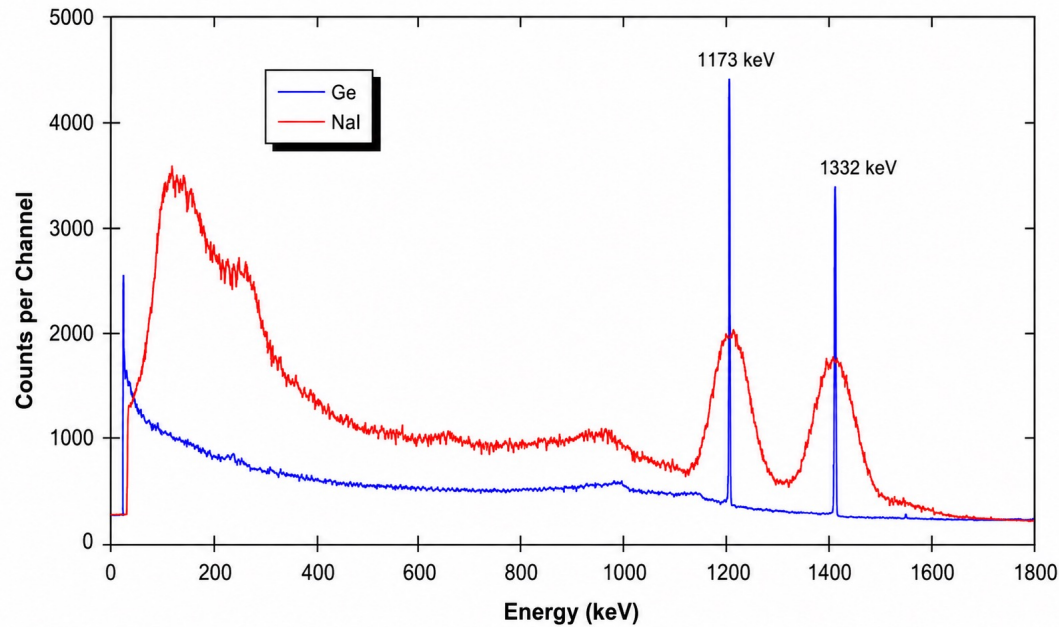
- Energy resolution: capability of separating two subsequent radiation signals by a distance greater than their FWHM
- FWHM: full width at half maximum of the peak, ΔE
- The resolution is usually given in terms of FWHM.
- Energies which are closer than this interval are usually considered unresolvable.

$$\text{Resolution} = \frac{\Delta E}{E_0} = \frac{FWHM}{E_0}$$



Nal: Scintillator detector (Inorganic)

Ge: Semiconductor detector



$E_0 = 1332 \text{ keV}$

$FWHM(\text{NaI}) = 70 \text{ keV}$

$FWHM(\text{Ge}) = 2 \text{ keV}$

$$R = 100 \times \frac{FWHM}{E_0}$$

Calculate the energy resolutions for red and blue detectors.
Which colour would you choose?

How to obtain FWHM?

The photopeak is often well described by a **Gaussian**

$$G(E) = \frac{A_p}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(E - \mu)^2}{2\sigma^2}\right]$$

$$\text{FWHM} = 2.355\sigma$$

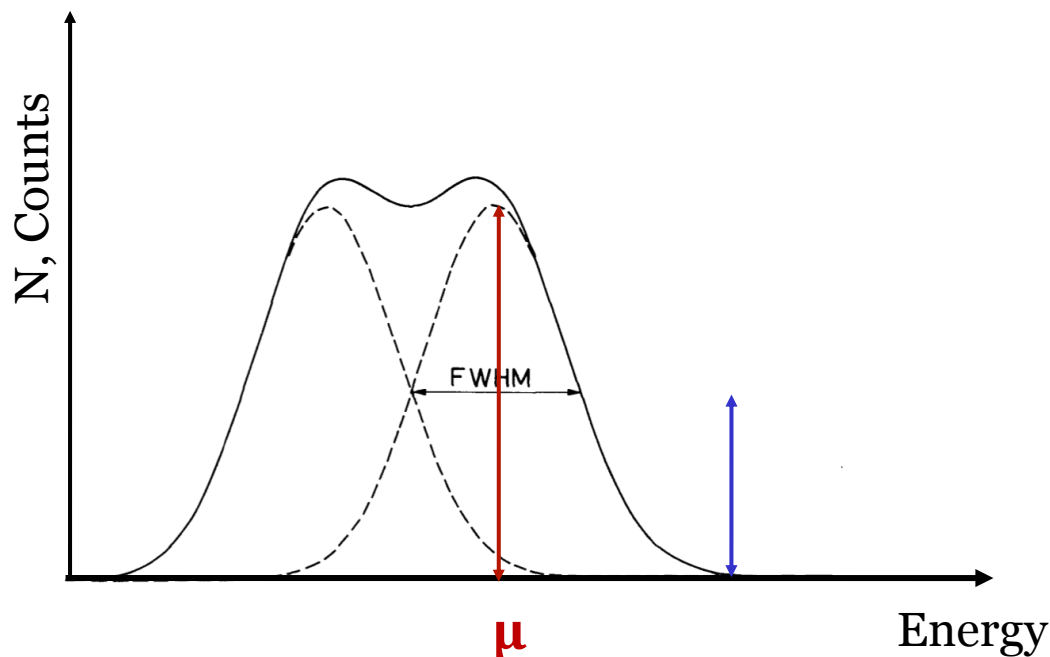
where,

A_p : peak area or number of counts,

σ : standard deviation,

μ : fitted centroid (peak position/energy)

$$\text{FWHM} = 2.355\sigma$$



1. Fit the peak with a Gaussian.
2. Obtain μ and σ .
3. Calculate **FWHM = 2.355 σ** .
4. Compute the resolution:

$$\text{Resolution} = \frac{\text{FWHM}}{\mu} = \frac{\text{FWHM}}{E_0}$$

Sources of fluctuations in the peak width, ΔE or FWHM

- ✓ **Statistical noise**, discrete nature of the measured signal (intrinsic resolution)
- ✓ **Random noise** within the detector and in the electronics processing the detector output signal
- ✓ **Drift** of the operating characteristics of the detector during the experiment.

$$(\text{FWHM})_{\text{overall}}^2 = (\text{FWHM})_{\text{statistical}}^2 + (\text{FWHM})_{\text{noise}}^2 + (\text{FWHM})_{\text{drift}}^2 + \dots$$

intrinsic resolution is an inherent property of the detector material such as gas, semi-conductor, scintillator (organic, inorganic)

In other words, the fluctuation will occur by the **intrinsic property** of a given detector type and thus we cannot avoid the statistical noise component in peak width.

Main factor is **number of ionizations/excitations** produced in the detector material, (not continuous but discrete) subject to random fluctuation from event to event

Resolution due only to statistical fluctuations in the number of ionizations/excitations = intrinsic resolution

Think about an incoming radiation with energy, E

The average energy required to produce an ionization is a fixed number, w .

- * w depends only on the material. (Will differ for different detector material!)
- * Remember “ w ” from BB formula?

Bethe (1930) & Bloch (1933)

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2m_e \gamma^2 v^2 W_{\max}}{I^2} \right) - 2\beta^2 - \delta - 2 \frac{C}{Z} \right]$$

Universal coefficients

$$2\pi N_a r_e^2 m_e c^2 = 0.1535 \text{ MeVcm}^2/\text{g}$$

r_e : classical electron
radius = $2.817 \times 10^{-13} \text{ cm}$

m_e : electron mass

N_a : Avogadro's
number = $6.022 \times 10^{23} \text{ mol}^{-1}$

I : mean excitation potential

Z : atomic number of absorbing
material

A : atomic weight of absorbing material

ρ : density of absorbing material

z : charge of incident particle in
units of e

$\beta = v/c$ of the incident particle

$\gamma = 1/\sqrt{1-\beta^2}$

δ : density correction

C : shell correction

$W_{\max}$: maximum energy transfer in a
single collision.

**Absorber
material**

**Incoming heavy charged
particle**

Resolution due only to statistical fluctuations in the number of ionizations/excitations

If we divide energy of the radiation E by w , we will get total (average) number of ionizations, J

$$J = E/w$$

E : energy of the incoming radiation

w : energy per one ionization

J : average number of ionizations

As energy increases, the number of the ionization events also increases resulting in smaller relative fluctuations.

Smaller the fluctuations better the energy resolution.

*Let's calculate **intrinsic resolution***
We will consider two different cases.

Suppose two identical 1332 keV γ rays enter the detector.
Will they produce exactly the same number of ionizations?

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For J $\rightarrow$ σ_J

Poisson limit

For a detector in which the radiation energy is not totally absorbed, the number of signal-producing reactions is given by a Poisson distribution.

Mean number of events, J = variance

$$\sigma^2 = J$$

$$J = E/w$$

$$R = 2.35 \frac{\overbrace{\sqrt{J}}^{\sigma_j}}{J} = 2.35 \sqrt{\frac{w}{E}}$$

$$R = 2.35 \sqrt{\frac{1}{J}}$$

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$$R = 2.35 \sqrt{\frac{1}{J}}$$

Scintillator detectors ($F=1$)

non-Poisson (statistical limit)

If the full energy of the radiation is absorbed as is the case for detectors used in spectroscopy experiments, the Poisson statistics is incorrect.

The resolution of many such detectors is actually smaller than that calculated from Poisson statistics. (fano factor, F)

$$\sigma^2 = FJ$$

$$R = 2.35 \frac{\sqrt{FJ}}{J} = 2.35 \sqrt{\frac{Fw}{E}}$$

$$R = 2.35 \sqrt{\frac{F}{J}}$$

Proportional counters, solid-state detectors $F < 1$

Fano factor:

The ***Fano factor*** has been introduced in an attempt to quantify the departure of the observed statistical fluctuations from pure Poisson statistics (in total average number of ionizations, J). It is defined as:

$$F = \frac{\text{Observed variance}}{\text{Poisson predicted variance}}$$

The ***Fano factor*** is 1 for Poisson statistics, and $\ll 1$ for non-Poisson statistics

Poisson limit

w energy per ionization (visible light creation) is 25 eV/photon for **NaI(Tl) Scintillator detector**

Calculate the mean number of charge carriers and the intrinsic detector resolution for 1332 keV gamma-ray energy.

Important warning:

Not all J events will be transmitted as signal but only 10% of it.

$$R = 2.35 \sqrt{\frac{1}{J}}$$

non-Poisson (statistical limit)

w energy per charge carrier (electron-hole creation) is 3 eV/photon for a **Germanium detectors**

Calculate the mean number of charge carriers and the intrinsic detector resolution for 1332 keV gamma ray energy.

Fano factor for Ge detectors is $F=0.12$

Compare the results with the previous case.

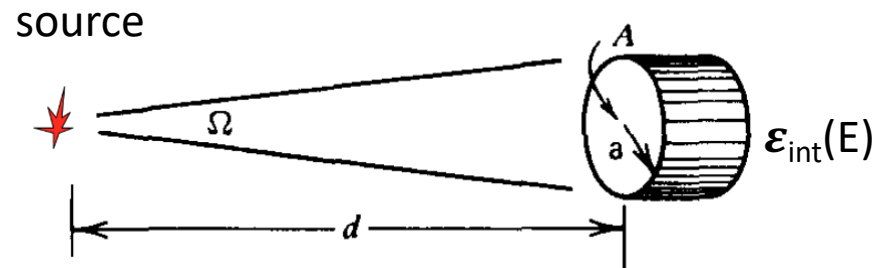
$$R = 2.35 \sqrt{\frac{F}{J}}$$



A (Area): number of counts under the peak

Detector efficiency

Detection efficiency represents the probability of detection for a single radiation quantum



the solid angle quantifies how large an object appears from a certain viewpoint, taking into account both its size and its distance. It is measured in steradians (sr).

$$\epsilon_{\text{abs}} = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta emitted by source}}$$

$$\epsilon_{\text{int}} = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta incident on detector}}$$

$$\epsilon_{\text{abs}} = \epsilon_{\text{int}} \frac{\Omega}{4\pi}$$

Ω : Solid angle of the detector seen from the actual detector position. (both polar and azimuthal angles)

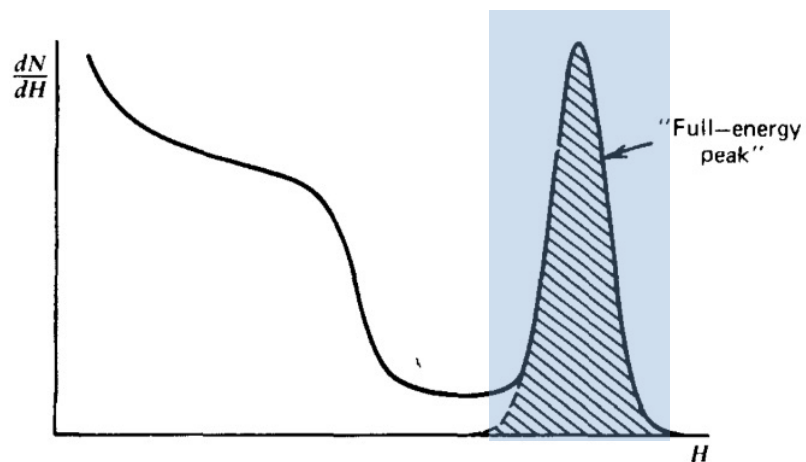
$$\epsilon_{abs} = \epsilon_{int} \frac{\Omega}{4\pi}$$

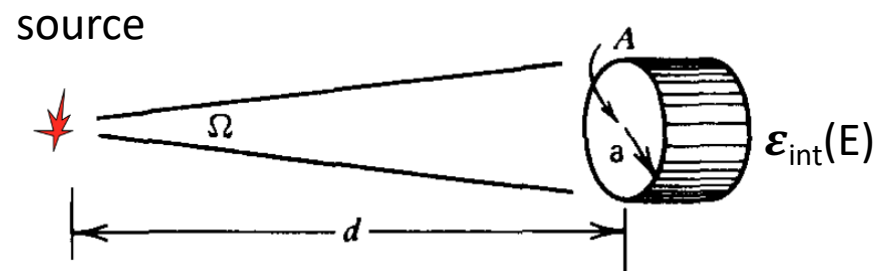
$$\epsilon_{int} = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta incident on detector}}$$

$$\epsilon_{abs} = \epsilon_{ip} \frac{\Omega}{4\pi}$$

$$\epsilon_{ip} = \frac{\text{number of events under the peak}}{\text{number of radiation quanta incident on detector}}$$

ϵ_{ip} : intrinsic peak efficiency





$$\epsilon_{abs} = \epsilon_{ip} \frac{\Omega}{4\pi}$$

$$\Omega = \iint \sin \theta \, d\theta d\varphi = 2\pi \left(1 - \frac{d}{\sqrt{d^2 + a^2}}\right) [sr]$$

For $a \ll d$

$$\Omega \cong \frac{A}{d^2} = \frac{\pi a^2}{d^2}$$

if d is larger, total efficiency decreases and by d^2 !!!

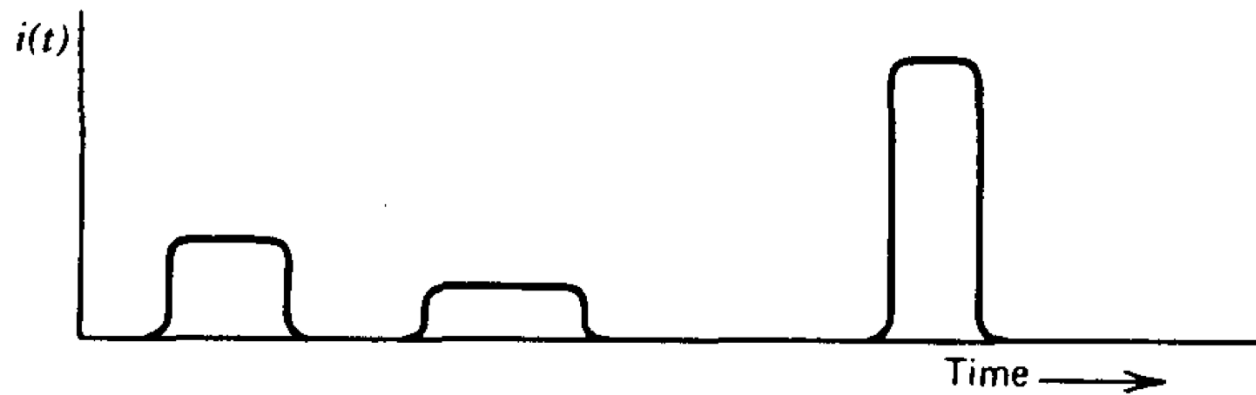
$$\epsilon_{abs} \approx \epsilon_{ip} \frac{a^2}{4d^2}$$

if detector is large (a is large), total efficiency increases.

*A desired detection system should have both **good energy resolution** and **efficiency**. But in practice, this is rather not the case. A good compromise has to be made according to the priority of the experiment.*

Dead time

If the event rate is not high, each detection event can be well separated and analyzed.



τ : dead time

(semiconductor) (ion chambers)
 electron-ion collection time, t_c (ns-ms) (detector response time)
 pulse processing time ($1\mu s$ - $5\mu s$)
 ADC conversion time
 event builder (CPU) time } (1 - $100\mu s$)

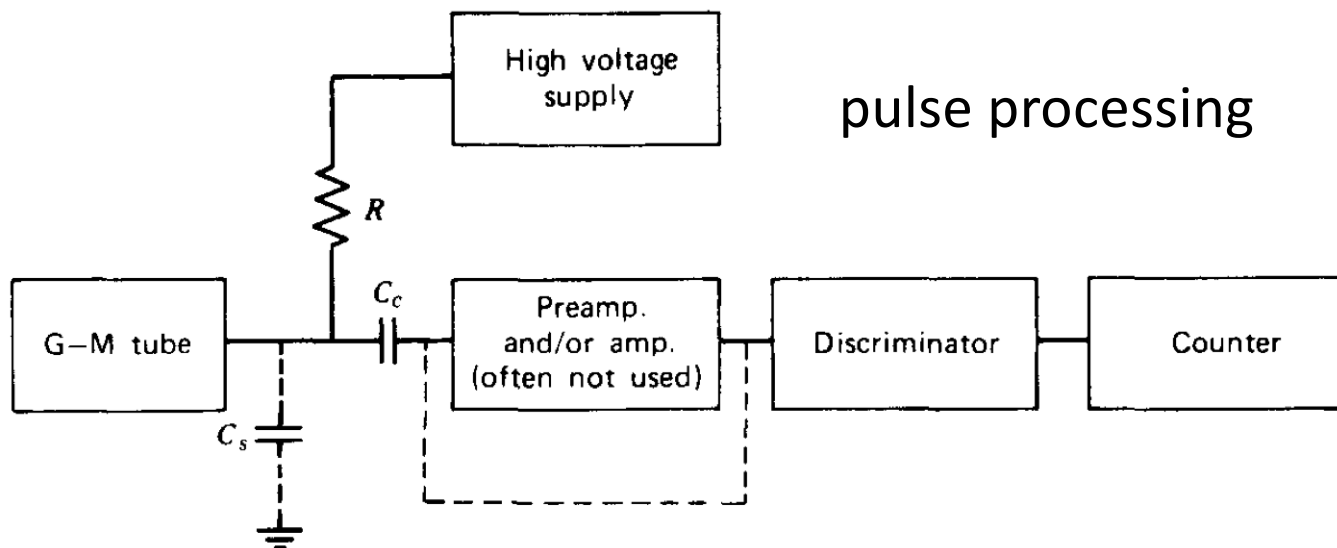


Figure 7.7 Block diagram of the counting electronics normally associated with a G-M tube.

Summary:

Detector property

High efficiency

Good resolution

Short dead time

Important when...

Counting weak sources

Identifying isotopes

High count rates

Key Messages

- Every detector begins with **radiation interacting with matter**.
- Different detector materials respond differently.
- The interaction creates a measurable signal.
- The choice of detector depends on the application.
- Next lecture: **Ionization detectors (Gas-filled)**.

Questions to you

- Why is energy resolution important for a given radiation? Can you give an example of “poor” and “good” resolution?
- What is the Fano-factor and how is it related to the FWHM energy resolution of detector?
- What is detection efficiency? What factors does the detection efficiency depend on?
- Why is the dead time of a detection system important? What are different contributions to the total dead time of a given measurement?
- Can a given type of detector be sensitive to all types of radiation? Explain the reasoning.