Nuclear Measurements

Nuclear and Reactor Physics Fundamentals

(BMETE80MX00)

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Contents

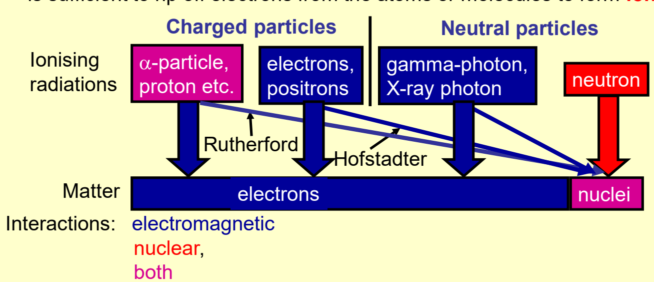
- Theoretical background (interaction of radiation with matter)
  - Charged particles (α-particle, electron/positron)
  - Neutral particles (γ- and X-ray photons, neutron)
- Detectors
  - Detection efficiency (geometric and intrinsic effiency)
  - Categorization of detectors
- Gas-filled detectors
  - ionization chamber,
  - GM-counter
  - Neutron detectors
- Scintillation detectors (solid and liquid)
- Semiconductor detectors (HPGe, PIPS)
- Gamma-spectroscopy
  - Energy resolution of the detectors
  - Qualitative and quantitative analysis, calibrations

Interaction between radiation and matter

We don't have senses to detect radioactive radiation directly.
(It's not just radioactivity: we don't detect ultrasound, ultraviolet radiation, radio waves, etc. directly)

In the following, we will only talk about ionizing radiation!

Ionizing radiation: energy transferred to matter in **one interaction** is sufficient to rip off electrons from the atoms or molecules to form **ions**.

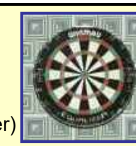


Estimate the probability of the interactions:

Radius of the electron shell: ~10^{-10} m, area: ~10^{-20} m²

Radius of the nucleus: ~10^{-14} m, area: ~10^{-28} m²

(the area of the nucleus is about hundred million times smaller)



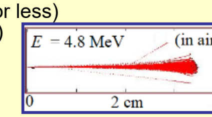
Conclusion: ionizing radiations **interact mainly with electrons** in matter (with the exception of neutrons)

Electrically charged particles ionize **directly**
Electrically neutral particles ionize **indirectly** (via special interactions) **!!!**

1) Interaction of electrically charged heavy particles with matter

(e.g. α-particle, proton…) „Heavy": $M >> m_{electron}$

Consequence:
- it penetrates into the matter in straight line (more or less)
- it ionises along its path (creates ion-electron pairs)
- it looses energy because of the ionization.



Matter: typical ionization energy: **~1-10 eV**,
α-particle: typical kinetic energy: **~1-10 MeV**
⇨ ~ 1 million ionization along its path until it stops

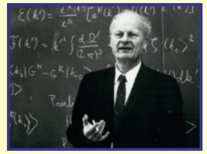
Linear Energy Transfer (LET)

(Bethe-Bloch equation)

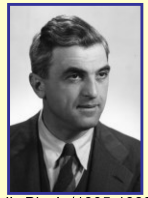
$$\boxed{\frac{dE}{dx} \cong \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \frac{4\pi \cdot N_A}{m_e} \cdot \left(\frac{z^2}{v^2}\right) \cdot \left(\frac{Z \cdot \rho}{A}\right) \cdot \cancel{X}}$$

Incoming particle
z: charge,
v: velocity
$N_A = 6 \cdot 10^{23}$

Parameters of material
ρ: density (1/m³),
Z: mean atomic number
A: mean mass number



Hans Bethe (1906-2005)
Nobel prize: 1967



Felix Bloch (1905-1983)
Nobel-prize: 1952

$\frac{dE}{dx} > 0$ is the energy **given to the material**

Of course, the incoming particle looses as much energy too, i.e. $\frac{dE_\alpha}{dx} = -\frac{dE}{dx}$

Note, that $\frac{dE_\alpha}{dx} \sim -\frac{1}{v^2} \sim -\frac{1}{E_\alpha}$

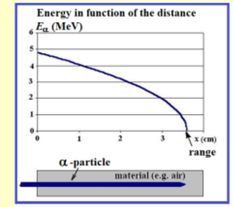
$$\boxed{\frac{dE}{dx} = \text{const} \cdot \left(\frac{z^2}{v^2}\right) \cdot \left(\frac{Z \cdot \rho}{A}\right)}$$

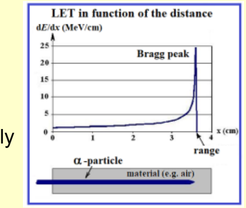
This is a differential equation for $E_\alpha(x)$

The solution is: $E_\alpha(x) = E_0 \sqrt{1 - \frac{x}{R}}$

Initial energy range

From this the LET: $\frac{dE}{dx} = -\frac{dE_\alpha}{dx} = \frac{E_0}{2R} \cdot \frac{1}{\sqrt{1 - \frac{x}{R}}}$





The α-particle gives off most of its energy to the material **at the end** of its path!

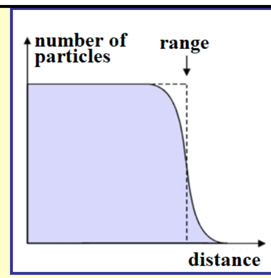
In reality the particles get scattered slightly. Therefore the Bragg peak gets less sharp.

High mass particles get scattered only slightly
$\longrightarrow$ sharp peaks
Lighter particles get scattered more
$\longrightarrow$ wider peaks

How does the particle beam decrease?

The figure shows how many particles reach a given distance from the surface of the material

Definition of the range:
the centre of the stopping region



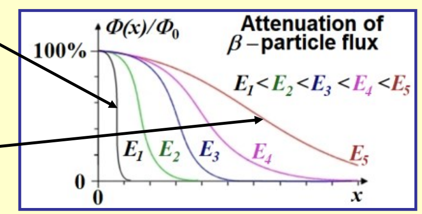
2) Interaction of electrically charged light particles with matter

(e.g. electron, positron…)

Similar to the Bethe-Bloch equation, BUT…
- the mass of the colliding particles are the same (electron with electrons), therefore there are also large angle scattering $\longrightarrow$ the particle beam spreads very quickly;
- high-energy electrons also have other processes (e.g. bremsstrahlung) $\longrightarrow$ the equation contains more terms

Penetration of β-particles (electrons) in the matter

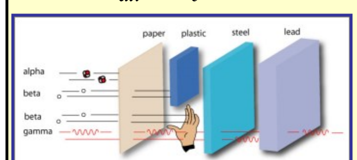
- Small energy β-particles: similar behaviour as for the α-particles (range concept is useful)
- high energy β-particles: similar to the γ-rays (see later)



Note: in the Bethe-Bloch equation

$\frac{dE_\alpha}{dx} \sim -\frac{1}{v^2}$ $\Longrightarrow$ For the same kinetic energy: $\left(\frac{1}{2}mv^2\right)$

- the velocity of the electrons are higher
- …results in lower LET
- …and **larger range**



alpha - a thin paper sheet absorbs it
beta - few mm material sheet absorbs it
gamma – only thick lead or thick concrete

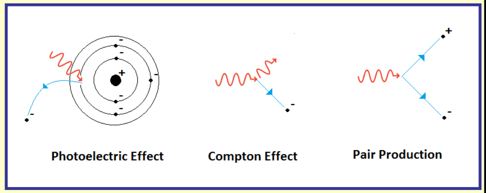
Interaction of gamma (and X-rays) with the matter

a) The energy quanta of the gamma- and X-rays are **photons**. Classically they are electromagnetic „waves": they interact mostly with the **electrons** of the atoms or molecules.

b) The interaction is a **stochastic process**, with relatively **small cross-section** (as compared to the ionization process of the charged particles) ⟶ long range!

c) **3 main types of photon-electron individual interactions**

- Photoelectric effect
- Compton scattering
- Pair production



Total γ-energy given to the electron

Only part of the γ-energy given to the electron

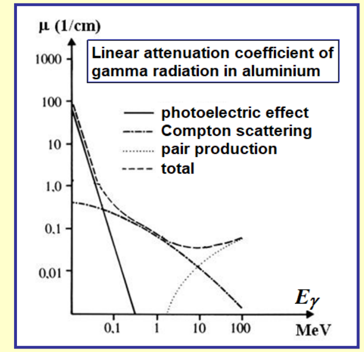
$E_\gamma \geq 1022$ keV

A relatively high energy charged particle (e^- or e^+) is created in all of them!

Attenuation of gamma-rays follow the exponential law

$$\boxed{\phi(x) = \phi_0 \cdot e^{-\mu \cdot x}}$$

Absorption of gamma radiation can be a complex function of gamma energy due to the 3 different processes: $\boxed{\mu = \mu(E_\gamma)}$



Knowledge of radiation absorption is important

- when designing **radiation shields**
- for the operation of **detectors**
- for **medical** applications (radiotherapy)

Interaction of neutrons with the matter

Neutrons are electrically neutral and therefore only ionize **indirectly**: they create electrically charged, high-energy particles in matter, via nuclear interactions (**nuclear reactions**)

Neutrons can interact only with **nuclei** (not with the electrons).

Because the cross-section is small ⟶ exponential attenuation

Two types of processes may take place:

- elastic scattering (charged particles get knocked-on)
- nuclear reaction

With **elastic scattering** neutrons can transfer significant amount of energy only for light nuclei. The most important is collision with protons.

For **nuclear reactions** the **exotherm** ones are most important, because they create high-energy charged particles, which can be detected easily.

For example: $^{10}B + n \longrightarrow {}^{4}He + {}^{7}Li + 2{,}79$ MeV

$^{235}U + n \longrightarrow$ fragments + neutrons + 200 MeV

The cross-sections are high for slow neutrons!

Detectors

- Their operation is based on the interaction of radiation with matter.
- They amplify the signal resulting from the interaction of radiation with the matter to a macroscopic scale.

The effects of the energy released in the material can be:

- Ionization ⟶ ionization chamber, GM tube
- chemical or physicochemical change ⟶ photo emulsion, cloud chamber
- excitation of atoms/molecules, followed by emission of a light flash ⟶ **scintillation detectors**
- creation of electron-hole pairs ⟶ **semiconductor detectors**

Penetration depth of radiation	Difficulty of detection
Very small (e.g. Low energy β, or α-particles)	Difficult, because the radiation is absorbed before it reaches the sensitive volume of the detector
Very large (e.g. neutrino, or very high energy particles)	Difficult, because the radiation has a small LET value, so it only gives off very little energy in a small volume. It can only be detected in huge volumes (and dense material)

Detection efficiency

Total detection efficiency:

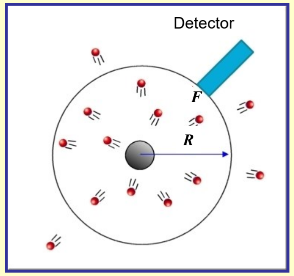
$$\varepsilon_{total} = \frac{\text{(number of detected particles)}}{\text{(number of emitted particles)}}$$

The total detection efficiency contains two terms:

Geometrical efficiency:
It describes that not all of the particles emitted from the source reach the detector.

For a point source and small area detector it can be determined easily: $\varepsilon_G = \dfrac{F}{4\pi R^2}$

Here R is the distance of the detector from the source, F is the surface area of the detector (perpendicular to the line toward the source)



Intrinsic efficiency
The detector usually does not detect all particles that fall on it.
(Some of the long-range particles pass through the detector)

$$\varepsilon_{int} = \frac{\text{(number of detected particles)}}{\text{(number of particles that reach the detector)}}$$

The **total efficiency** is the product of the two : $\varepsilon_{total} = \varepsilon_G \cdot \varepsilon_{int}$

Categorization of the detectors

Detectors showing traces of the particles

- Photo emulsion

film dosimeter

- Solid state track detector
- Cloud chamber
- Bubble chamber
- Multi-wire proportional chamber (MWPC) – particle physics

Particle „counters"

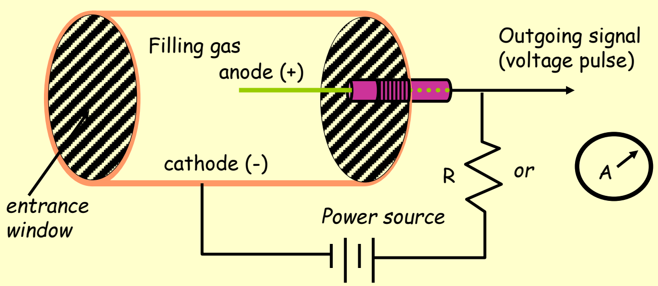
- **Gas-filled counter**
  - Ionisation chamber
  - proportional chamber
  - Geiger-Müller counter (GM-counter)
- **Scintillation detector** (crystal, liquid)
- **Semiconductor detector**
  - HPGe (high purity germanium)
  - Ge(Li), Si (Li) detector
  - Surface layer detector (PIPS)

Particle counters

1. Gas filled counters

How does that work?

- The ionizing particles create electron-ion pairs in the gas
- The electric field between the electrodes separates and collects the separated charges → an electric pulse is created.
- The electric pulse is amplified electronically
- The amplified pulses are processed (counted, their amplitude measured, etc.)

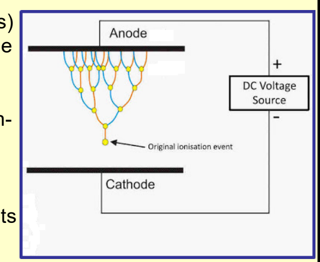


Two modes of operation:
- Pulse-mode (counting, measuring the amplitudes of the counts etc.)
- Continous current (high intensity radiations, e.g. nuclear reactor)

Two important processes in the gas

1) **Recombination** works against charge collection (ions meet electrons again). Therefore strong electric field is required to collect the separated charges completely

2) **Gas-amplification** (avalanche-process)
- Large electric field → electrons get large kinetic energy while flying freely before colliding again with another gas atom
- They ionize again, creating new electron-ion pair
- This way it is possible to collect more charge than originally created by the incoming particle → electric pulse gets amplified



Types of gas-filled detectors:

- Ionisation chamber
  - We collect all the primary charges and ions, but only that!
  - Low amplitude signals, high post-amplification required.
  - Suitable for measuring the energy deposited by the particle in the gas counter
- Proportional chamber
  - gas amplification still in the proportional region
  - Signals with larger amplitudes
  - Still suitable for measuring the energy of the particle (calibration needed)
- Geiger-Müller counter (GM-counter)
  - very large gas amplification,
  - signals with large amplitudes,
  - signal amplitude is not depending anymore on the energy deposited in the gas
  - Not suitable for measuring the energy, only for counting!

Neutron detectors (problem: counting only neutrons, nothing else)

1) BF_3 counter

A proportional chamber filled with boron trifluoride (BF_3) gas.

$^{10}B+n \longrightarrow {}^4He + {}^7Li$ + 2,79 MeV

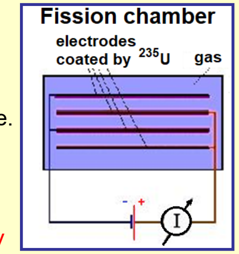
The created charged particles (^4He and ^7Li) receive the energy, they ionize the gas strongly $\longrightarrow$ the chamber emits a pulse.

2) ^3He counter

A proportional chamber filled with ^3He gas

$^3He+n \longrightarrow {}^3H + {}^1H$ + 0,76 MeV

The created charged particles (^3H and ^1H) ionize the gas $\longrightarrow$ the chamber emits a pulse.



3) Fission chamber

A proportional chamber, containing ^{235}U-coated metal electrodes.

^{235}U +n $\longrightarrow$ fragments +neutrons + 200 MeV

High-energy fission fragments strongly ionize the gas $\longrightarrow$ the chamber emits pulses (or current can be measured).

Detection of **high-energy neutrons**: first slow them down, then detect.

Scintillation detectors

In some materials, tiny light flashes (scintillation) occur when energy is received from the impacting radiation.

- Fluorescence - instant flash ($t < 10^{-18}$ s)
- ~~Phosphorescence - delayed light emission ($t > 10^{-18}$ s)~~

The scintillating material can be

- solid
- liquid
- gas
- inorganic
- organic

Scintillation was discovered and used already when nuclear physics began: Spinthariscope (1903 W. Crookes)

A thin layer of ZnS could be watched through a magnifying glass. Some small amount of radium was mixed (Ra is α-particles emitter). In ZnS, tiny flares (scintillations) were generated by α-particles.

Commonly used scintillation detectors in nuclear measurements

Inorganic scintillator crystals

Most of them are ionic crystals, some alkali halide (alkali metal and halogen compound)

- NaI(Tl) sodium iodide (doped with thallium)
- CsI(Tl) caesium iodide (doped with thallium)
- LiI(Eu) lithium iodide (doped with europium)
- CaF_2(Eu) calcium fluoride (doped with europium)

Doping elements are in very small quantity (only „traces")

- Concentration of e.g. Eu is only ~1/1000 in the crystal
- They are the „activators", they assure the scintillation

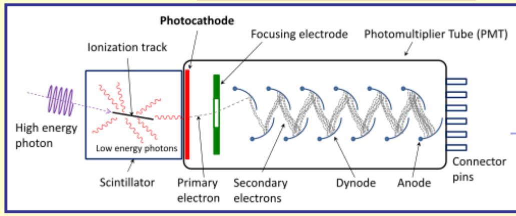
Large sizes can be grown from crystals

Dual advantage: high atomic density (solid), large size $\longrightarrow$ High efficiency γ-detector!

Scintillation is no longer being watched with naked eye!

Photomultiplier devices are used

Scintillation detector




photomultiplier

The detection process of a γ-photon:

- The γ-photon interacts with the scintillator material: it transfers energy to an electron (Compton scattering, photoeffect, pair production)
- The generated electron transfers its energy to the crystal along its ionization track (dE/dx) and stops (or escapes if the crystal is small)
- The crystal responds to the transferred energy by scintillation. Visible photons are emitted. The **number of photons** is proportional to the energy transferred to the crystal (!)
- The visible photons leave the crystal and enter the photomultiplier
- The photomultiplier converts them to an **amplified electric pulse**
  The pulse amplitude is proportional to the number of visible photons

Scintillation detector

Procedure summarized:

γ-ray → photo-effect, Compton-scattering, pair productions → electron → energy deposited in crystal → number of visible photons } crystal

number of visible photons → amplitude of the anode signal } PM tube

Structure of a scintillation γ-detector

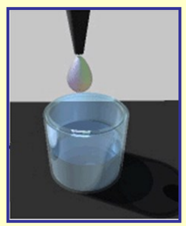
Scintillation crystal (replaceable)

PM-tube + electronics

(covered by very thin metal foil for α, and/or β-detection)

Liquid scintillation detector

Liquid scintillation measurement technology is most commonly used to measure **environmental** samples for the detection of **low β-energy** and **low-activity** radioisotopes (^{3}H, ^{14}C, ^{35}S, ^{32}P), or **α-emitters.**



Advantage: **high detection efficiency** especially for low-energy β-rays and for α-rays

A scintillator is usually an organic liquid (cocktail) into which **the sample is mixed**

The cocktail consists of several components:

- solvent,
- scintillator compound ("fluorine")
- emulsifier, etc.

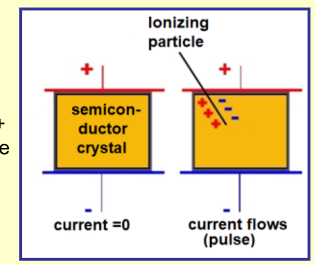
The scintillation flashes from the transparent cuvette containing the cocktail and the sample are detected by 2 PM-tubes inside the device.

Name of the commercially available equipment: **TriCarb** (tritium and radiocarbon)

Semiconductor detectors

Principle of the detection:

- High voltage is applied to the semiconductor crystal
- Because it is an insulator, no electricity flows
- The ionizing radiation creates electron+ hole excitations in the electron-structure
- The applied electric field collects the charges ⟶ an electric pulse can be measured
- The amplitude of the pulse allows energy measurement



The amplitude of the pulse is proportional to the collected charges!

However, the detection is hampered by impurities and thermal excitation

According to the Boltzmann-distribution: $\boxed{n(E) \sim e^{-\frac{E}{kT}}}$

Here $n(E)$ is the number of particles with excitation energy E

Thermal excitation also creates electron-hole excitations ⟶ disturbs!

Comparison with the gas-ionization chamber

Ionization chamber	Semiconductor detector
The gas is good insulator	Medium electrical insulator (at room temperature)
The ionizing radiation creates electron-ion pairs	The ionizing radiation creates electron-hole pairs
Necessary energy for creating electron-ion pairs ~ 1 – 10 eV	Necessary energy for creating electron-hole pairs ~ 0,1 – 0,5 eV
The electric field collects the charges → electric pulse	The electric field collects the charges → electric pulse
Density of gas is small → small intrinsic efficiency	Density of a crystal is high → high intrinsic efficiency

The condition for detecting a small pulse is to have very small residual current → it should be a good insulating material !!!

Good insulation can be ensured with the following conditions:
- low temperature (liquid nitrogen temperature **cooled detector**)
- **high purity** material, → HPGe detectors or
- create a depleted layer, → Ge(Li), Si(Li) detectors

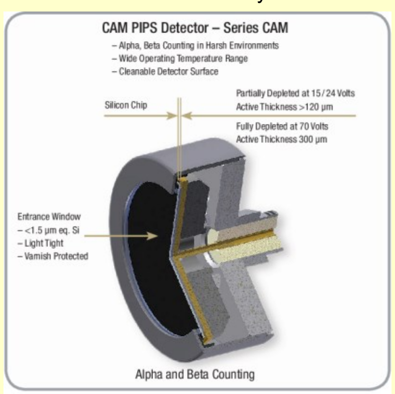
Most common semiconductor materials: **Ge, Si, GaAs**

Structure of a typical semiconductor detector:
(e.g. High purity germanium detector, HPGe)

Detector housing
preamplifier
heat conducting rod in vacuum
Dewar, containing liquid nitrogen

Passivated Implanted Planar Silicon (PIPS) surface-layer detector

Suitable for detecting short-range charged particles (mostly α-particles). The thin active detection layer is formed at the surface of the detector.



Excellent for detecting **α-particles**

Its small volume (small thickness) is an advantage:
Not sensitive to long-range radiation (e.g. gamma radiation), detects **only high LET** particles

Gamma-spectroscopy

Its importance:
- gamma rays come out of the sample, so they can be measured “from the outside” without destroying the sample (**non-destroying** method)
- **several elements** can be determined at the same time
- both **qualitative and quantitative** measurements are possible!

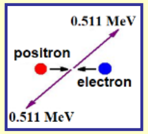
Remember: **only the energy delivered to the detector can be measured!**

Problem: due to the primary and secondary processes in the detector, **the spectrum has a rather complex structure**

Primary processes:
Photo effect (line-structure; it would be nice if only it was alone!)
Compton scattering (continuous energy distribution)
Pair-production (can be the starting point for secondary processes)

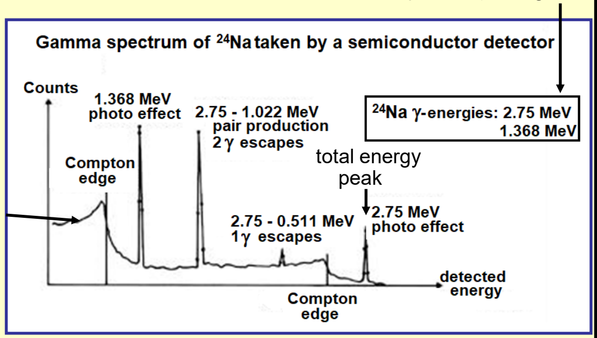
Secondary processes:
Compton scattering + photo effect → total gamma energy (good!)
pair production + positron annihilation → “escape” peaks
etc.…

Positron annihilation:
$e^+ + e^- \longrightarrow 2\gamma$
E_γ = 0,511 MeV

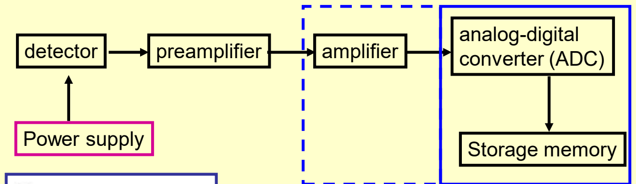


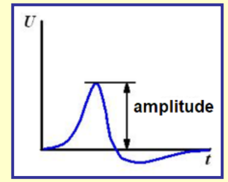
One isotope, two γ-energies

Complex spectrum



Scheme of a gamma-spectrometer





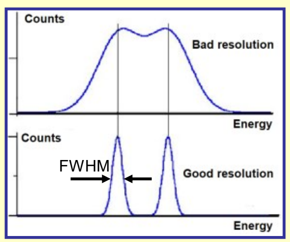
Pulse form from the detector

The amplitude (height) of the signals from the detector is proportional to the energy delivered in the detector: $U_{max} = k \cdot E + U_0$

Determination of the proportionality factors k and U_0: by calibration

Energy calibration: measurement of γ-sources (standards) of known energy

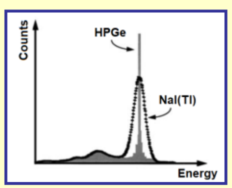
Important parameter for a gamma-spectrometer: energy resolution



The energy resolution is characterized by the „width" of the peak.

The „full width at half maximum" (**FWHM**)

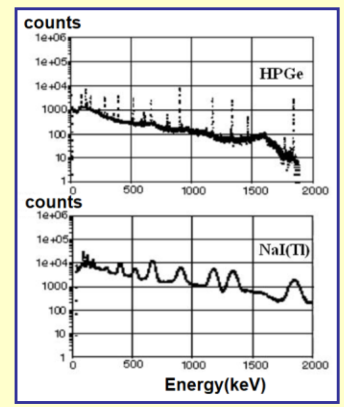
Comparison of the spectra of a scintillation and a semiconductor detector



	FWHM (at 1 MeV)
HPGe	1-2 keV
NaI(Tl)	80-120 keV

Comparison of the spectra of a scintillation and a semiconductor detector

Qualitative analysis:
Based on the **location (energy)** of the peaks, the emitting isotope can be determined.
Energy calibration required!
(calibration of the "X axis")



Quantitative analysis:
Based on the **area** of the peaks, the amount (concentration) of the emitting isotope can also be determined.
Efficiency calibration required!
(calibration of the "Y axis")

Thank you for your attention !

These slides are **uploaded** in the „Files" menu item of the Teams Group: *Nuclear and Reactor Physics Fundamentals*,
in Channel: *Nuclear Physics 5.*
Nuclear Measurements(5. November)

At the end of the slides there are some „*Self-test questions*". Please try to answer them to check your own understanding.

Self-test questions

1. What is the main form of energy-loss for an alpha-particle when it enters into some material?
2. Is the exponential attenuation law valid for alpha-radiation? Explain!
3. Compare the behaviour of alpha- and beta-radiation when they enter into some material!
4. What are the main interactions of gamma-rays with matter? Describe their main features!
5. What are the processes that enable detecting neutrons? Describe their features!
6. An α-detector (PIPS) has 2 cm^2 sensitive surface, and is placed in vacuum at 50 cm distance from a point-like radioactive source. Its intrinsic efficiency is 100%. We detect 100 counts/s. What is the activity of the α-source? Why is it necessary to place this experiment in vacuum?

Self-test questions (cont.)

7. What are the operational modes of gas-filled counters? Explain!
8. How do neutron-detectors work that are based on gas-filled counters? What is the energy range of the neutrons for which they are the most sensitive?
9. What processes take place until a γ-photon gets finally detected in a NaI(Tl) scintillation detector?
10. Why are γ-spectra so complex? What kind of peaks may appear in them? Explain!
11. What are the charge-carriers inside a semiconductor detector? How are they produced? About how much energy is needed?
12. Why a semiconductor detector needs to get cooled?
13. Compare a NaI(Tl) scintillation and a HPGe semiconductor detector performance, when detecting γ-rays!
14. What are the energy- and efficiency calibrations of a γ-detector?