Gamma-ray spectrometry basics #1:
What are gamma-rays and how can we measure them?

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NKS GammaSkill Training Day, 26.09.2023

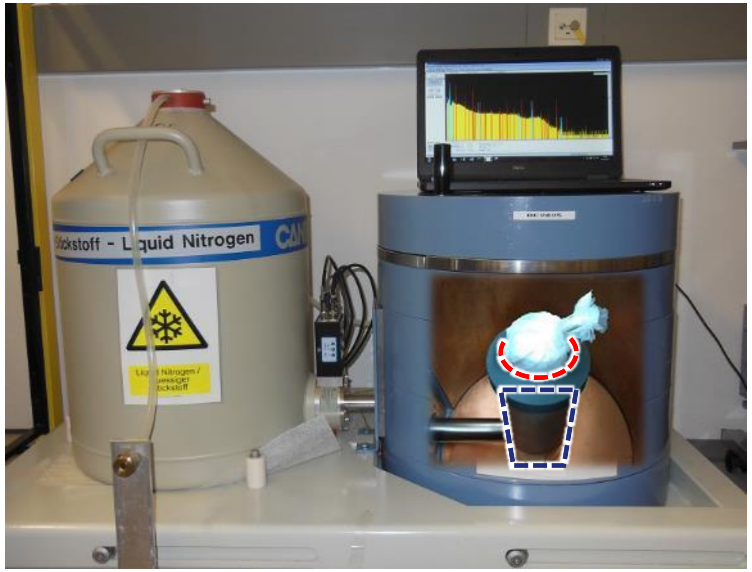
My history with gamma-ray spectrometry

- **2008:** Completed my studies with thesis on high energy photon beam dosimetry
- **2009-2016:** Responsible for operation of the accredited gamma-ray spectrometry laboratory at the DSA (then NRPA) in Østerås, Norway
- **2012-2013:** Short-term engagement at Qatar University to set up, calibrate and develop procedures for HPGe detectors at their environmental radioactivity lab.
- **2016-2021:** Gamma Spectrometry Specialist at IAEA Seibersdorf (TEL)
- **2021-now**: Establishing a laboratory for radiological characterization and waste classification to support the decommissioning process at IFE (Kjeller, Norway) focusing on gamma-ray spectrometry measurements

Agenda

What is gamma-ray spectrometry?

- A measurement technique for identification and quantification of gamma-ray emitting radionuclides, usually in some kind of **sample**, by using a suitable **detector**.

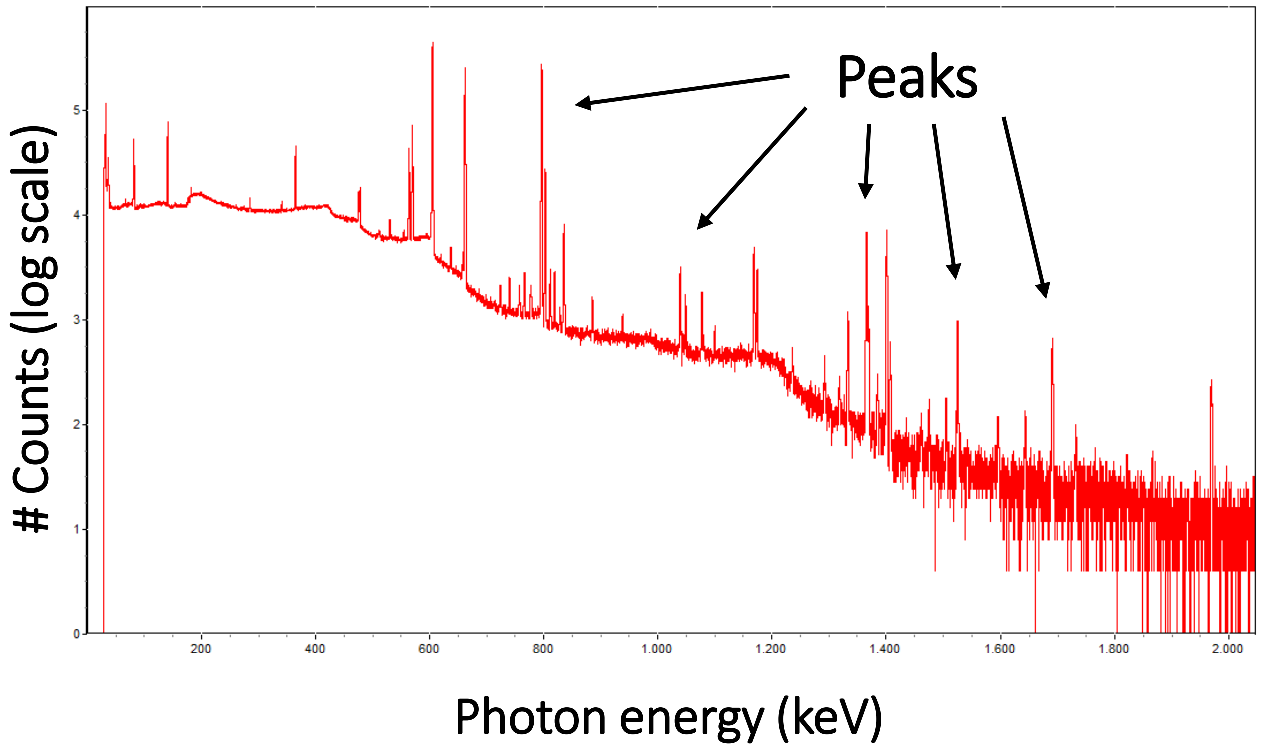


In the laboratory

In the field ("in situ")

What is gamma-ray spectrometry?

- Looking at the gamma spectrum output of the measurements, and using it to say something about the radionuclide content
  - **Which** radionuclides are present and **how much** radioactivity of each

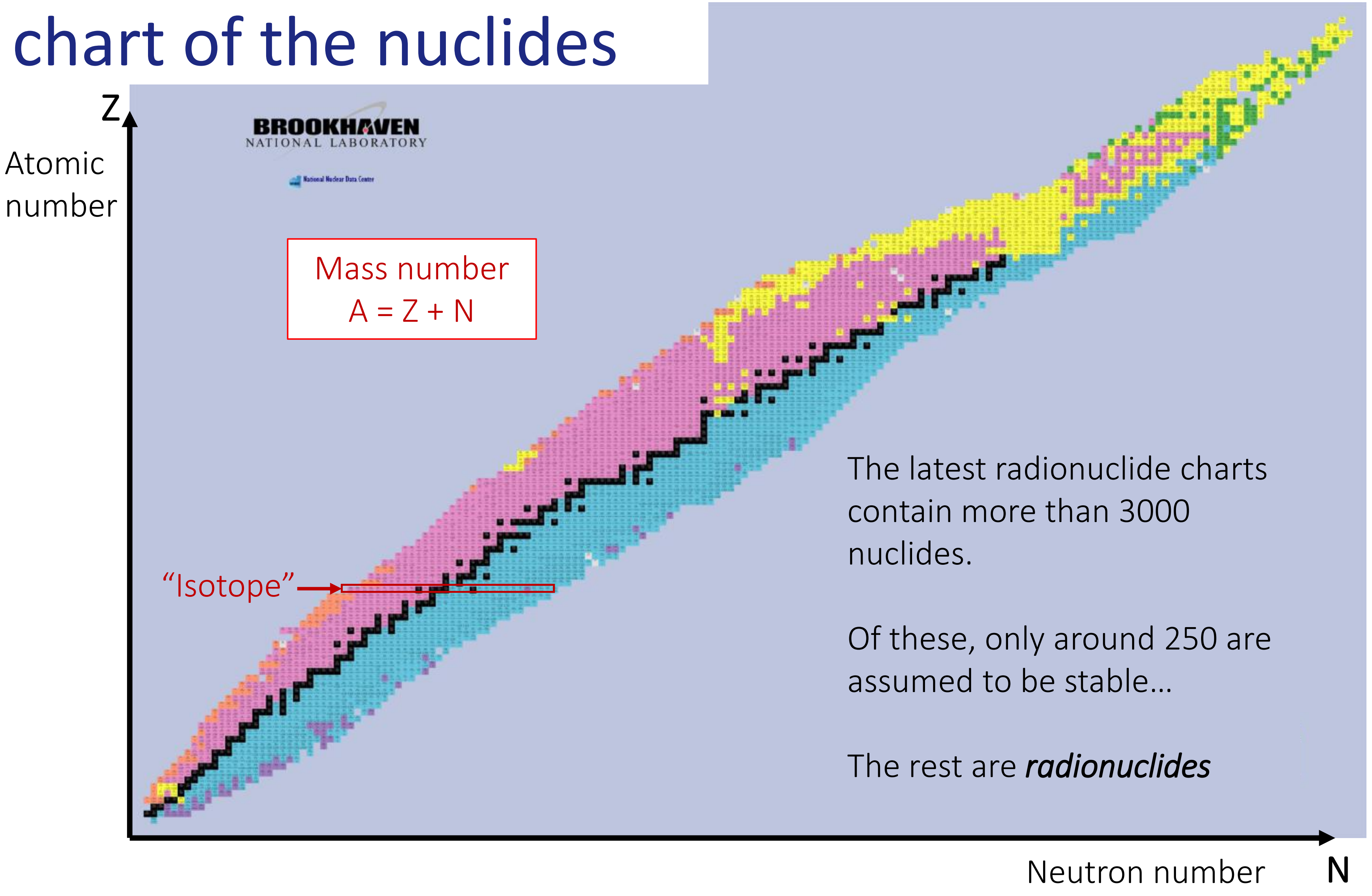


Various applications of gamma-ray spectrometry

- Environmental monitoring
- Emergency preparedness
- Radiation protection
- Nuclear security & safety
- Decommissioning
- Particle physics experiments
- Geo- and astrophysics
- Medical isotope production
- Neutron activation analysis
- …

Agenda

The chart of the nuclides



The latest radionuclide charts contain more than 3000 nuclides.

Of these, only around 250 are assumed to be stable…

The rest are ***radionuclides***

Main decay modes of the radionuclides

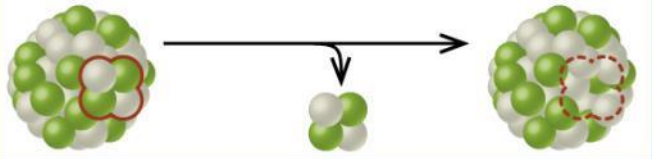
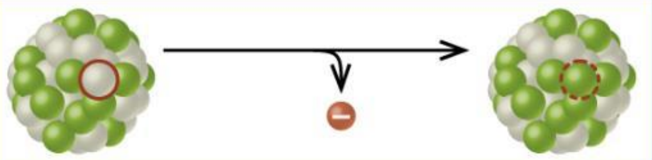
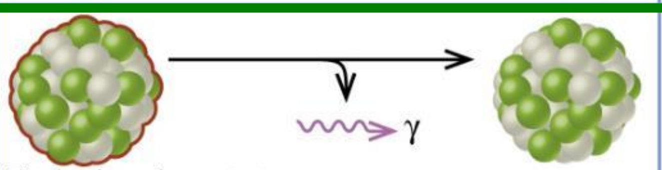
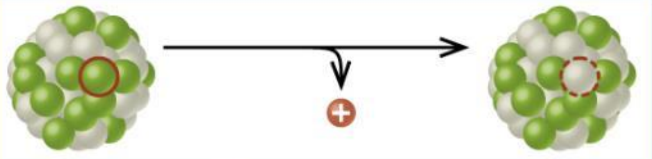
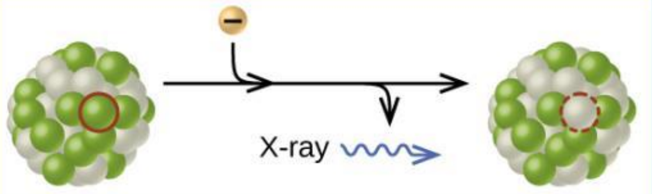
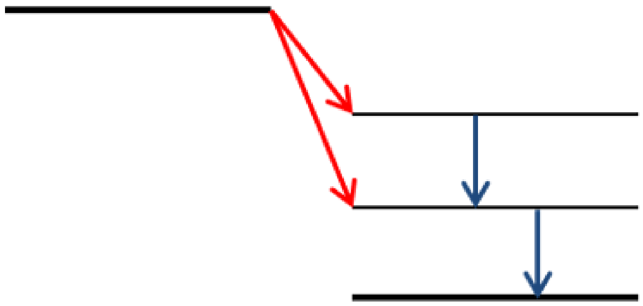
Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	$^{A}_{Z}X \quad ^{4}_{2}He + ^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	$^{A}_{Z}X \quad ^{0}_{-1}e + ^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	$^{A}_{Z}X \quad ^{0}_{0}\gamma + ^{A}_{Z}Y$		A: unchanged Z: unchanged
Positron emission	$^{A}_{Z}X \quad ^{0}_{+1}e + ^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1
Electron capture	$^{A}_{Z}X \quad ^{0}_{-1}e + ^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1

Figure source: https://opentextbc.ca/chemistry/chapter/21-3-radioactive-decay/

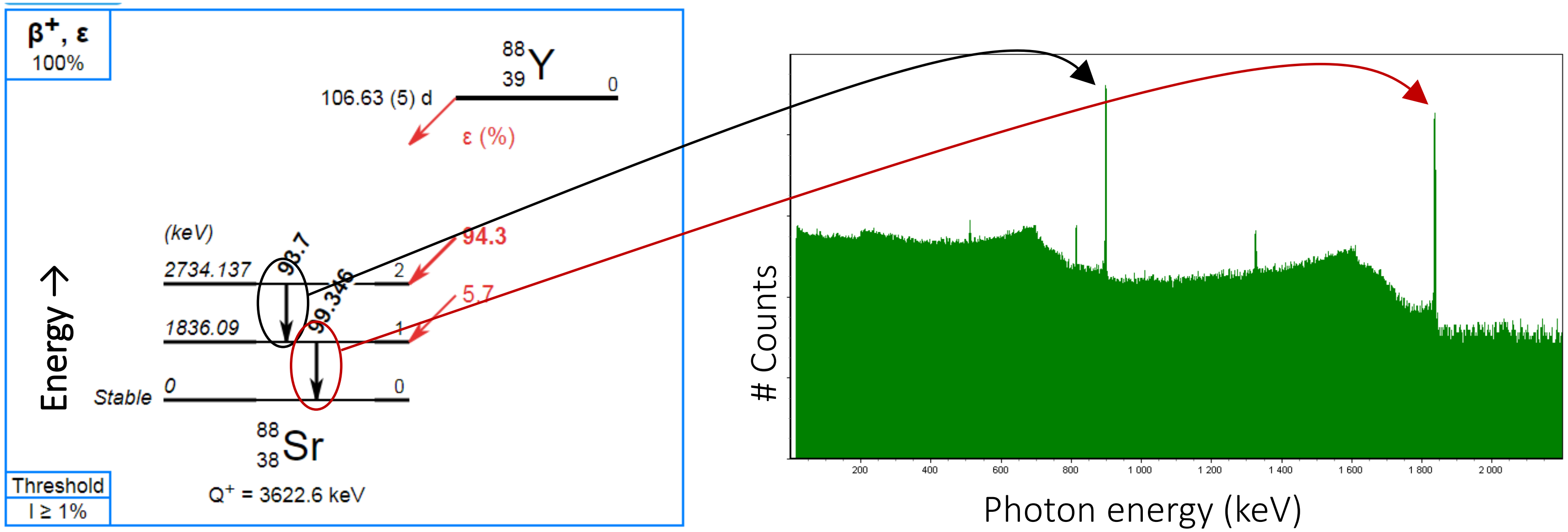
Some quick facts about gamma decay

- Consists of pure electromagnetic energy (zero mass, zero charge)
- Does not happen just by itself, but follows another decay process that leaves the nucleus in an excited nuclear state
- The energies of the emitted radiation to go from an excited state to the ground state are very strictly defined by a radionuclide’s **decay scheme**, and can be used as a “fingerprint” for detection of that radionuclide.



Measuring gamma-rays in a spectrum

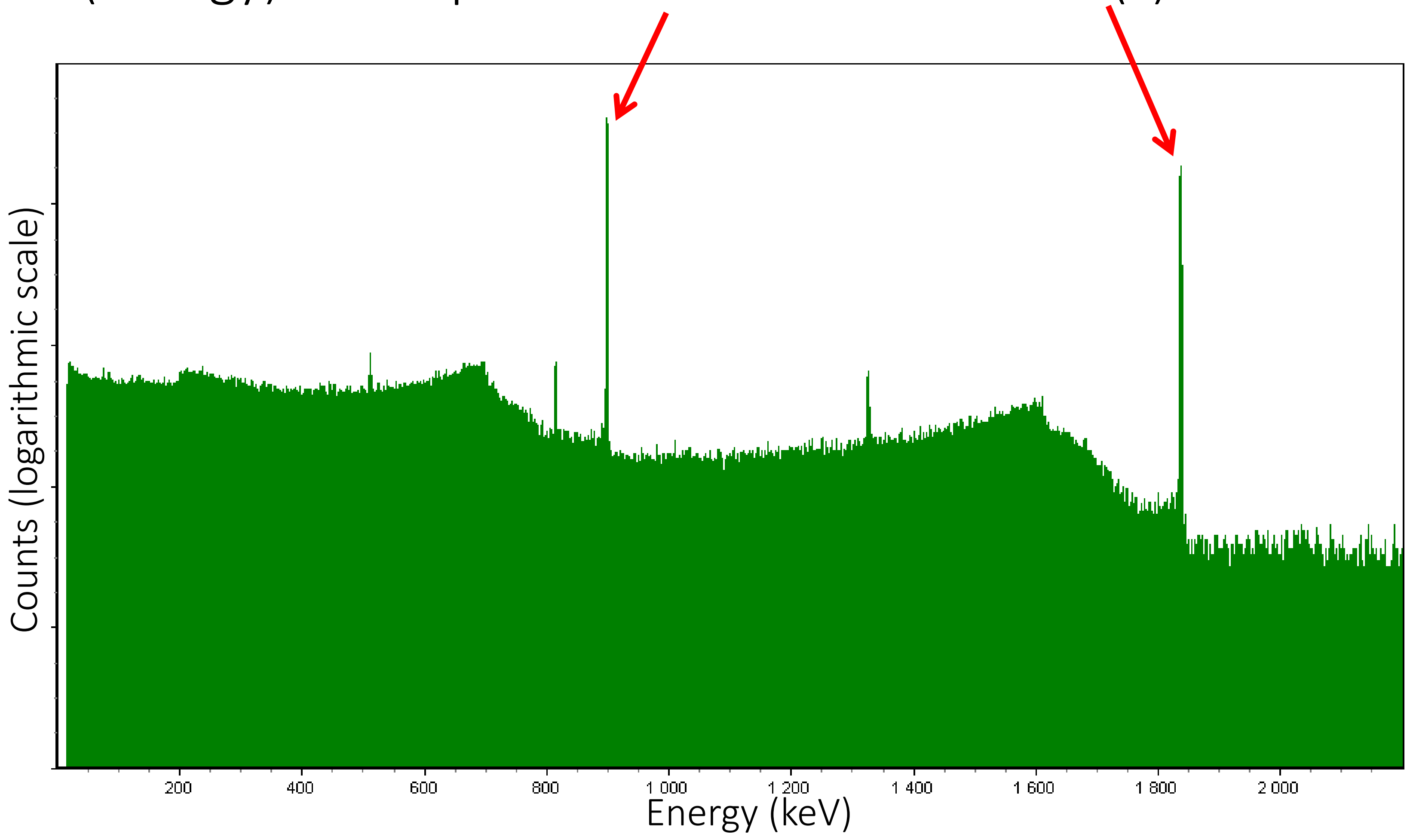
- Decay scheme for Y-88 (simplified):



- Emitted gamma-ray energies correspond to the energy differences between levels of the radionuclide's decay scheme
- Corresponding <u>full energy peaks</u> appear in the gamma spectrum

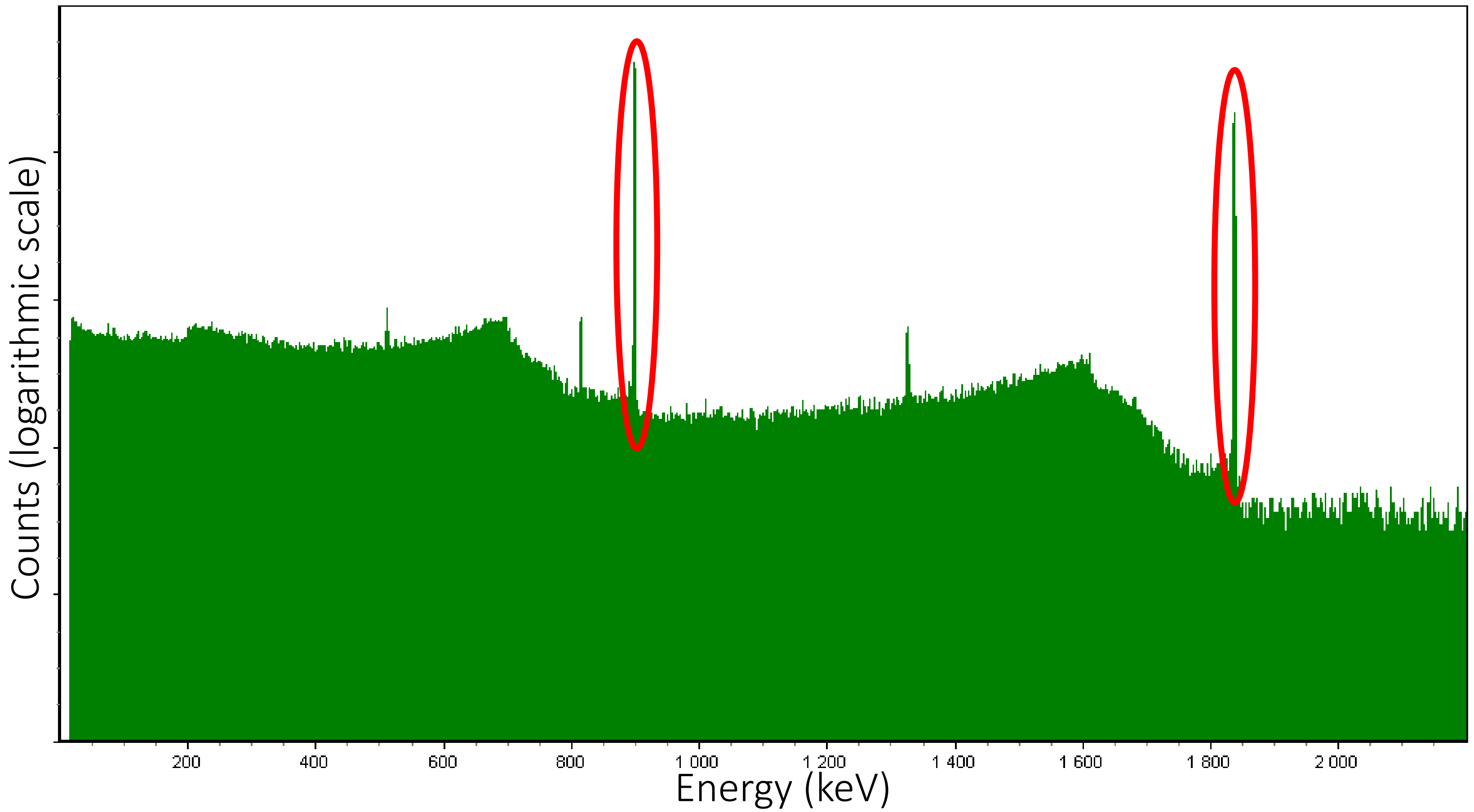
The gamma spectrum

- The location (energy) of the peaks tells us which nuclide(s) are in the spectrum



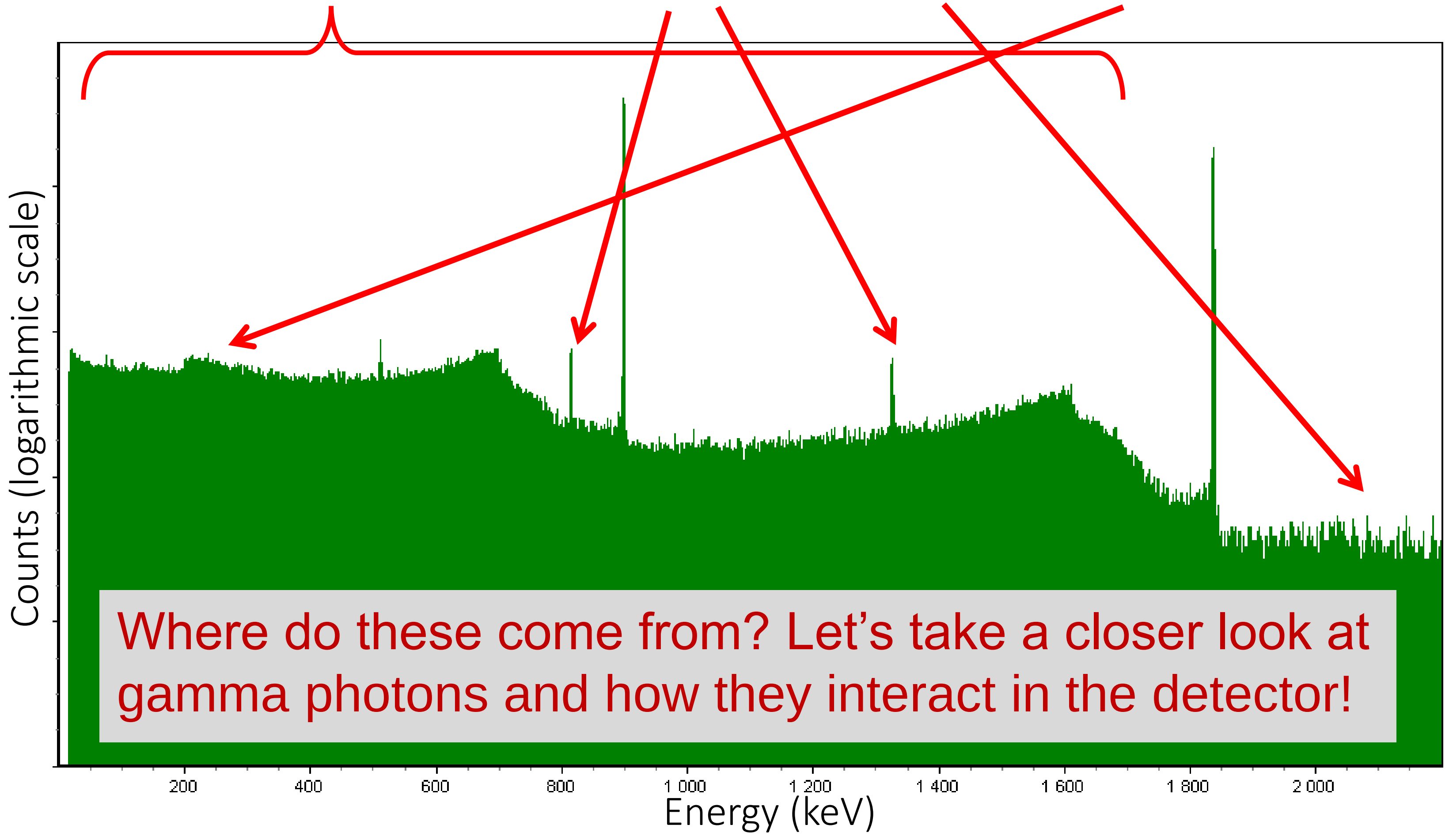
The gamma spectrum

- The **size (area)** of the peaks tells us something about the nuclide activity



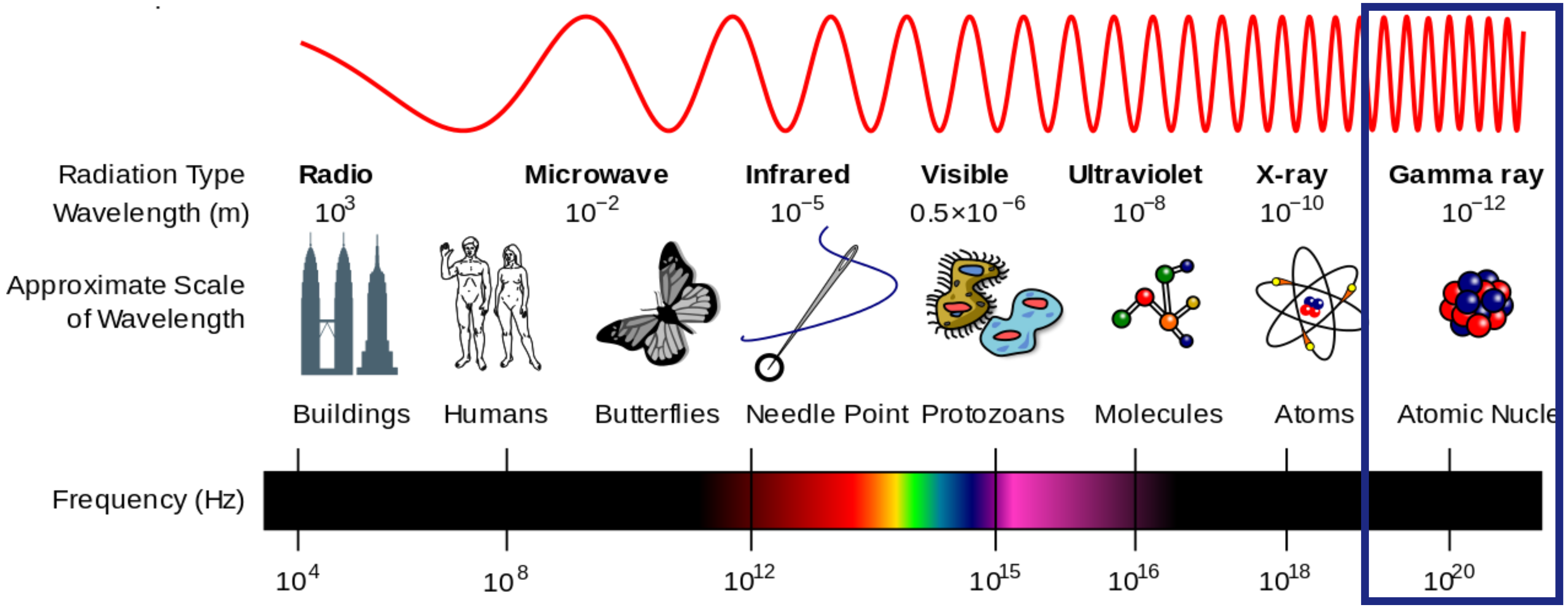
The gamma spectrum

- We can also see many other effects in the spectrum



Agenda

The electromagnetic spectrum

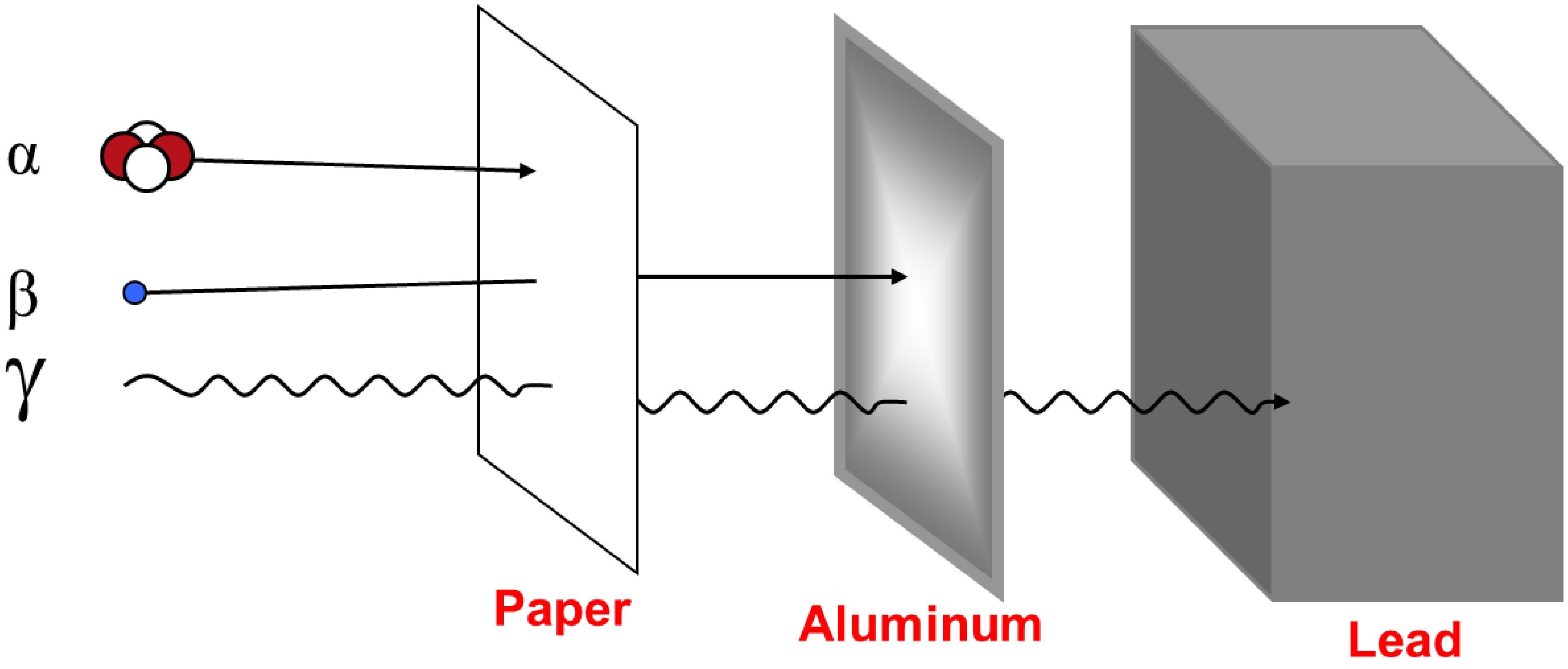


Gamma rays have frequency > 10^{19} Hz (wavelength < 100 pm)

→ corresponds to photon energy > 40 keV (10^{-14} Joule)

And remember: NO mass NO charge

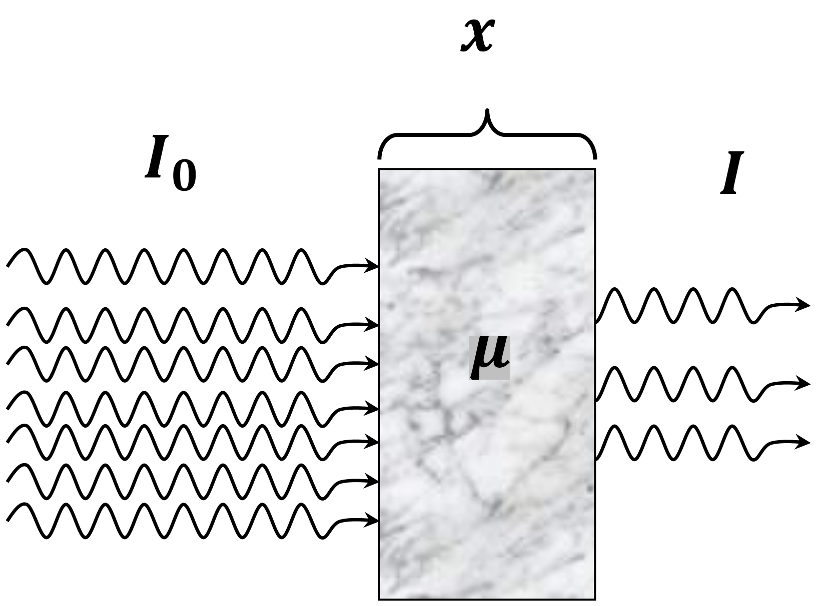
How do you stop a gamma-ray photon?



Photons do not have a fixed “stopping distance”, instead we need to consider the probability of interaction with the material they pass through.

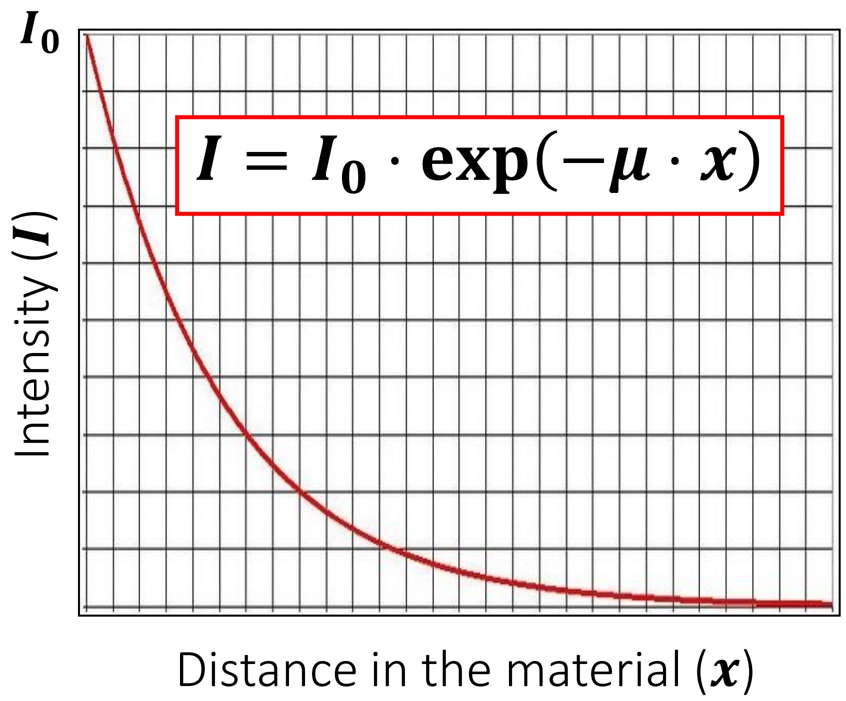
Attenuation of photons in a material

- Attenuation of a monoenergetic photon beam through a material:

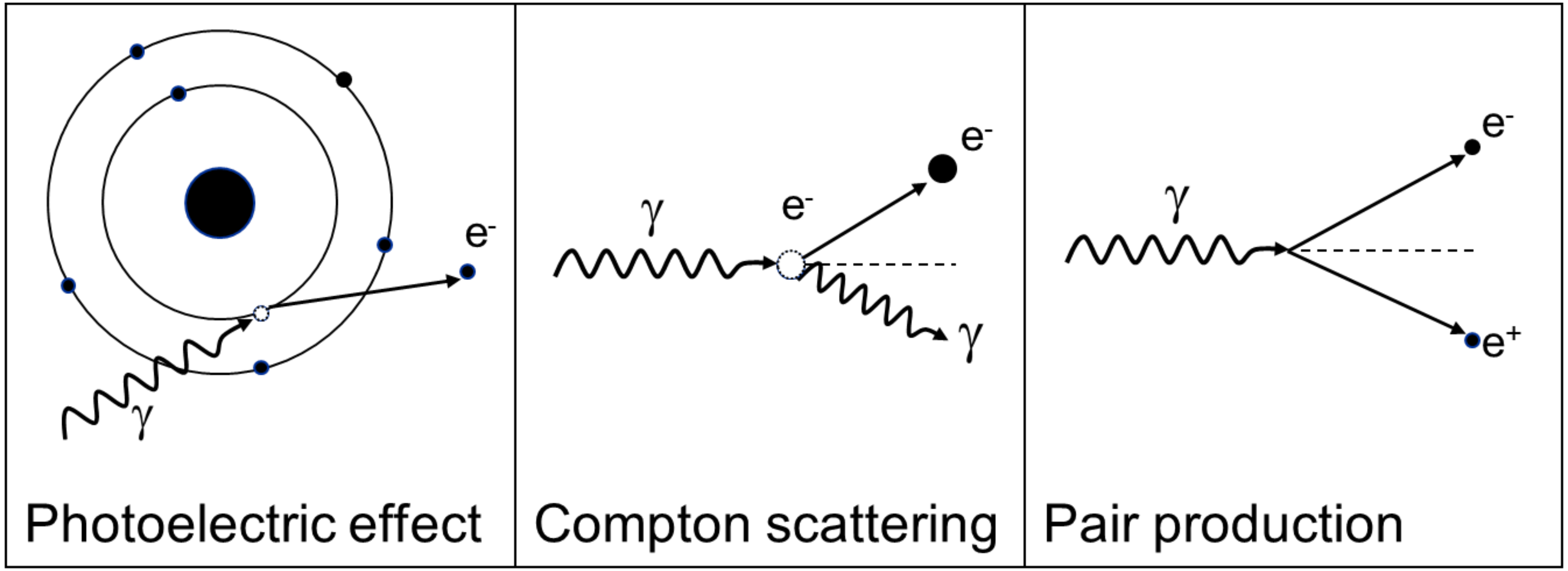


→ μ is the **linear attenuation coefficient** of the material at the photon energy of interest

- Plot of photon attenuation as a function of distance in the material:



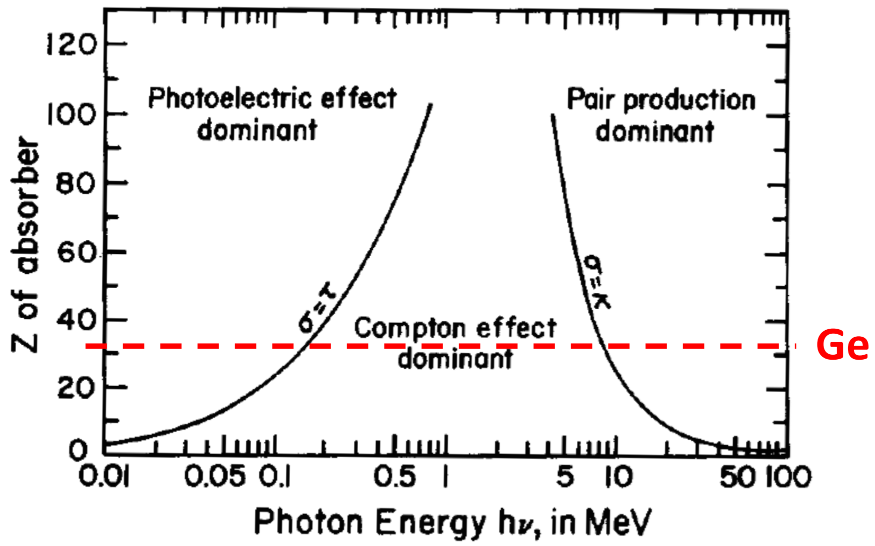
Types of photon interactions in a material

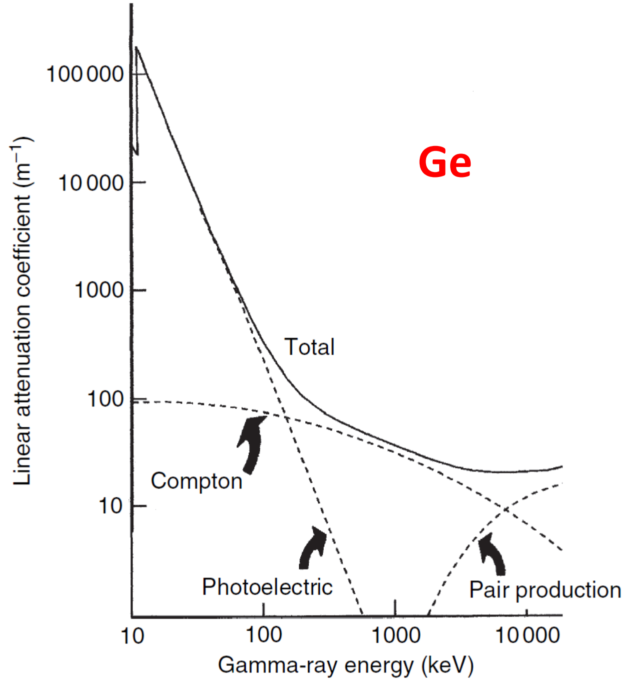


We will not cover each interaction mechanism in detail today, but you can read more in your favorite introductory radiation physics textbook!

Probability of different photon interactions

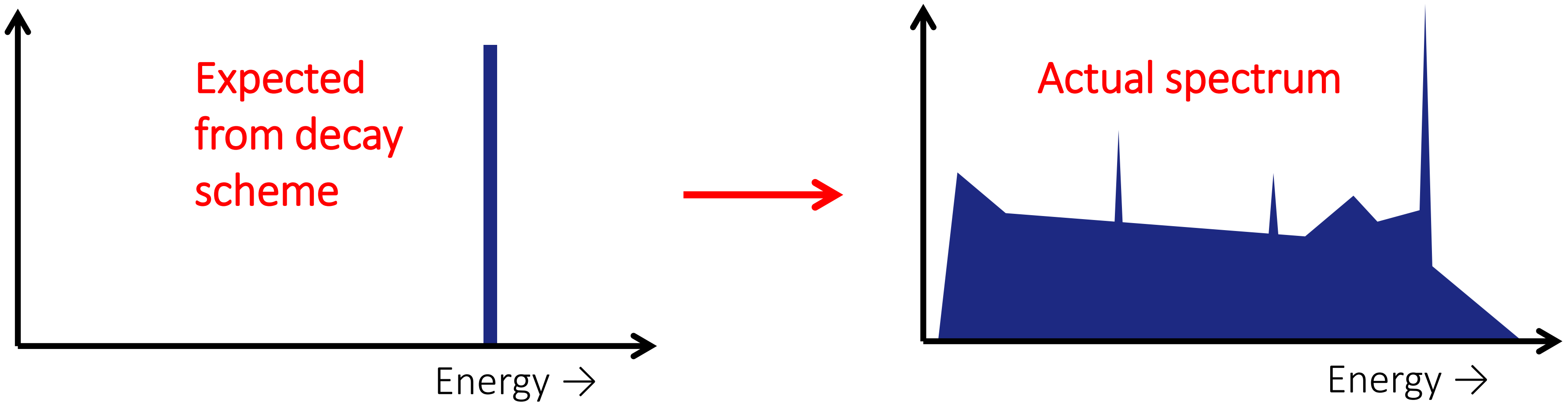
The three main interaction mechanisms have different probabilities for interaction depending on energy.





The gamma spectrum

- Due to the different photon interaction mechanisms, the spectrum is not a “perfect” picture of the radionuclide’s decay scheme
  - Photoelectric effect → signal to full energy peak
  - Compton scattering → signal to continuum
  - Pair production → escape peaks 511 keV and 1022 keV below the full energy peak ($E_\gamma > 1022\ \mathrm{keV}$)
  - Combination of multiple effects → signal can end up “anywhere”…



Example spectrum #1

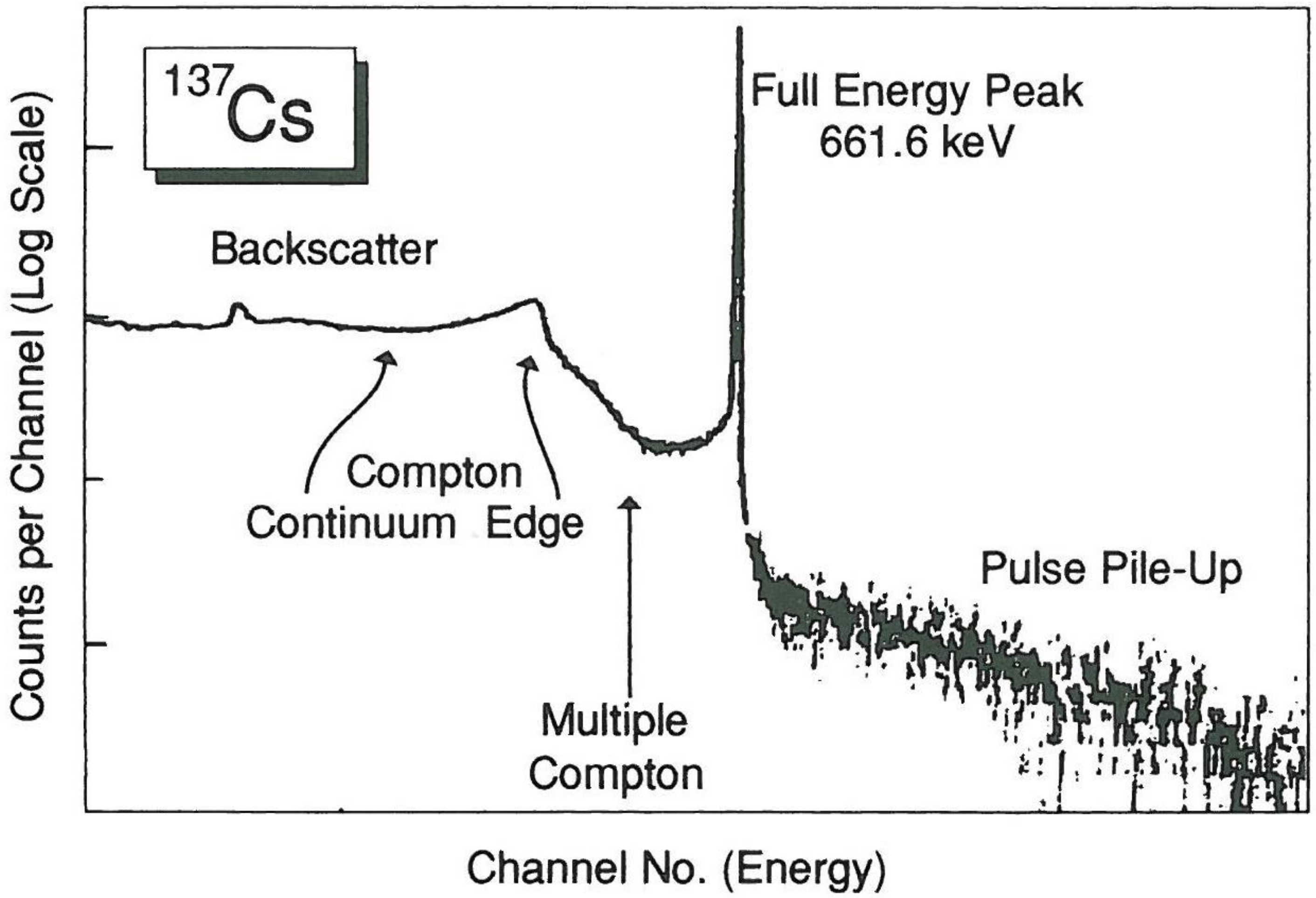


Figure source: Gilmore, 2008. "Practical gamma-ray spectrometry"

Example spectrum #2

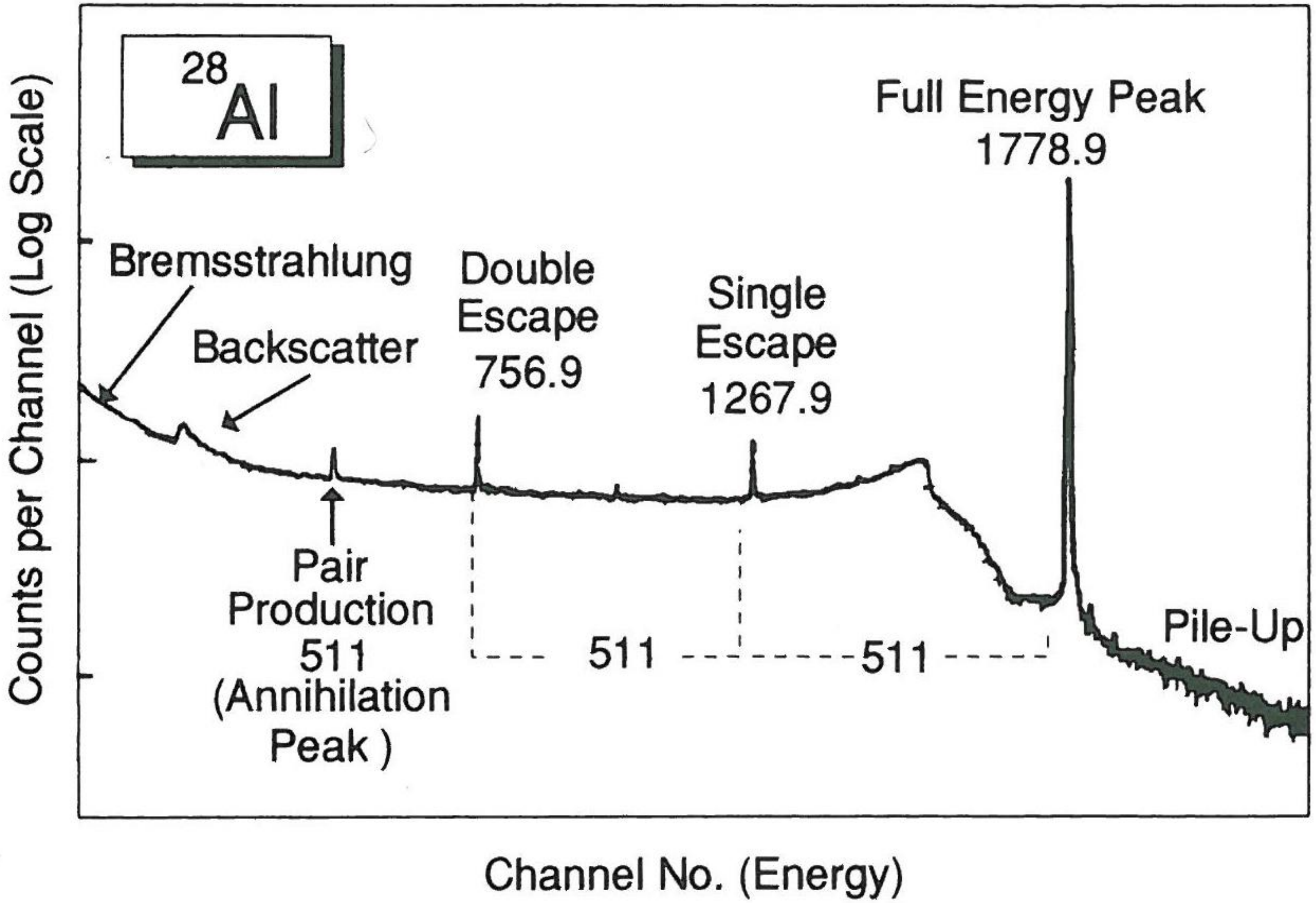
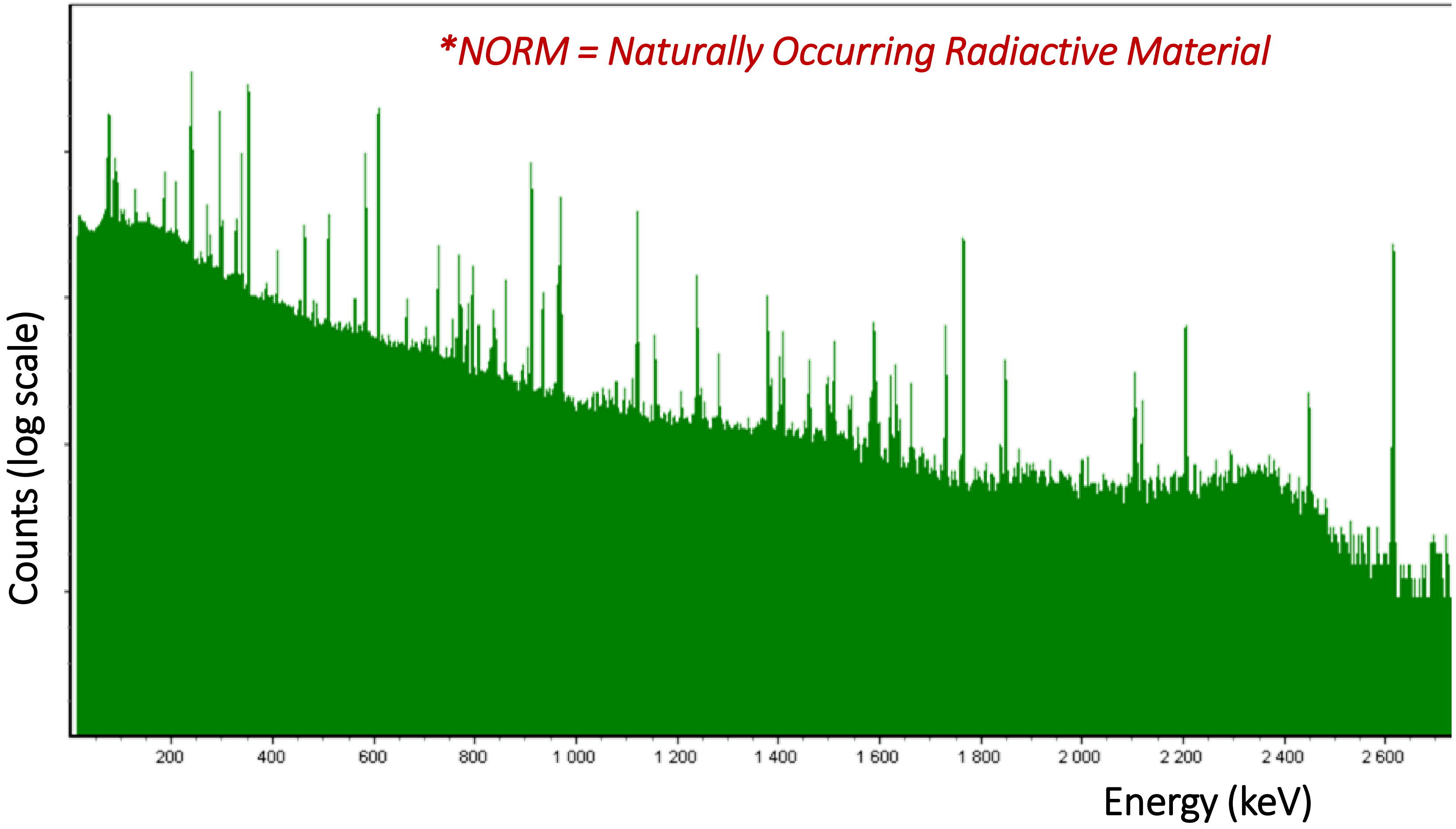


Figure source: Gilmore, 2008. "Practical gamma-ray spectrometry"

Some «real» spectra can get quite complicated…

- Example of a spectrum from a NORM* sample:

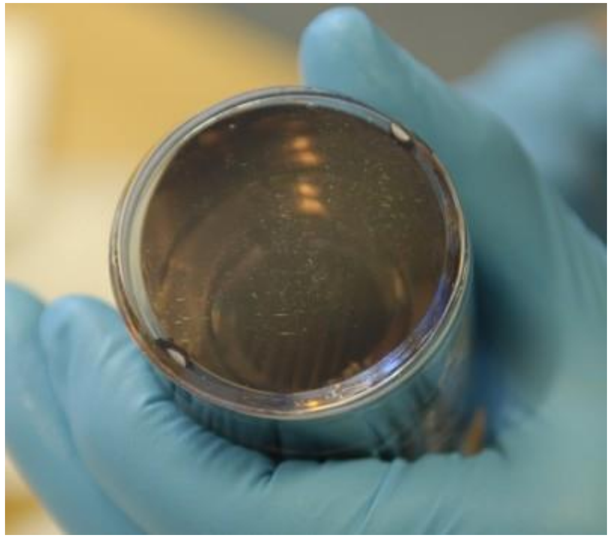


Agenda

Detector types for gamma-ray spectrometry

- There are two main detector types used for gamma-ray spectrometry:

1. Scintillation detector
   NaI, LaBr, CeBr, CsI, …



+
Relatively low cost
Large sizes possible
Fast signal processing
Robust

–
Bad peak resolution
Internal contamination (LaBr)
Temperature instability

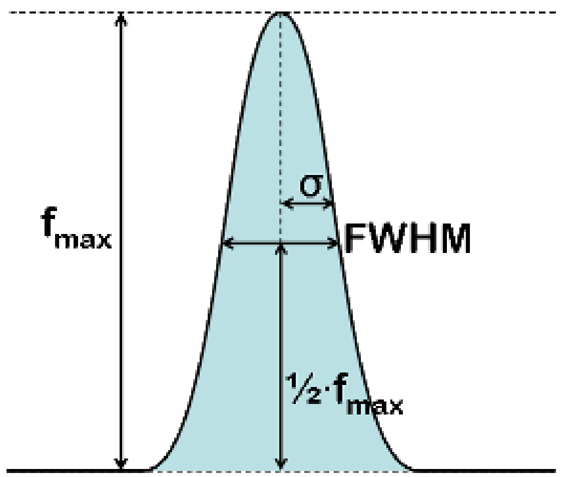
2. Semiconductor detector
   HPGe, Si, CZT

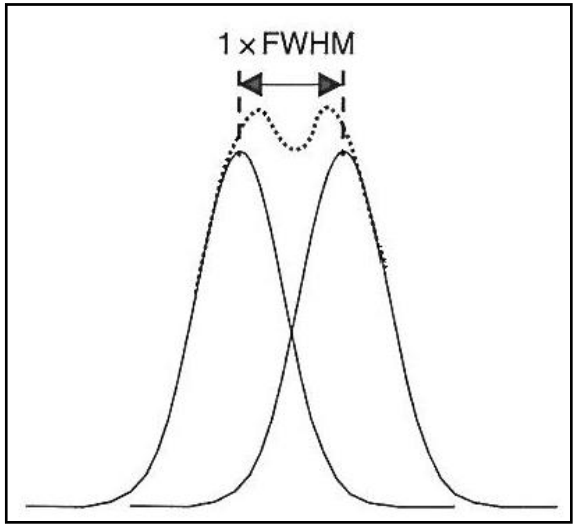
+
Superior peak resolution
Low "limit of detection"

–
Can be (very) expensive
Limited size possible
Require cooling (HPGe)
Fragile, can easily break

FWHM – a measure of spectrum peak resolution

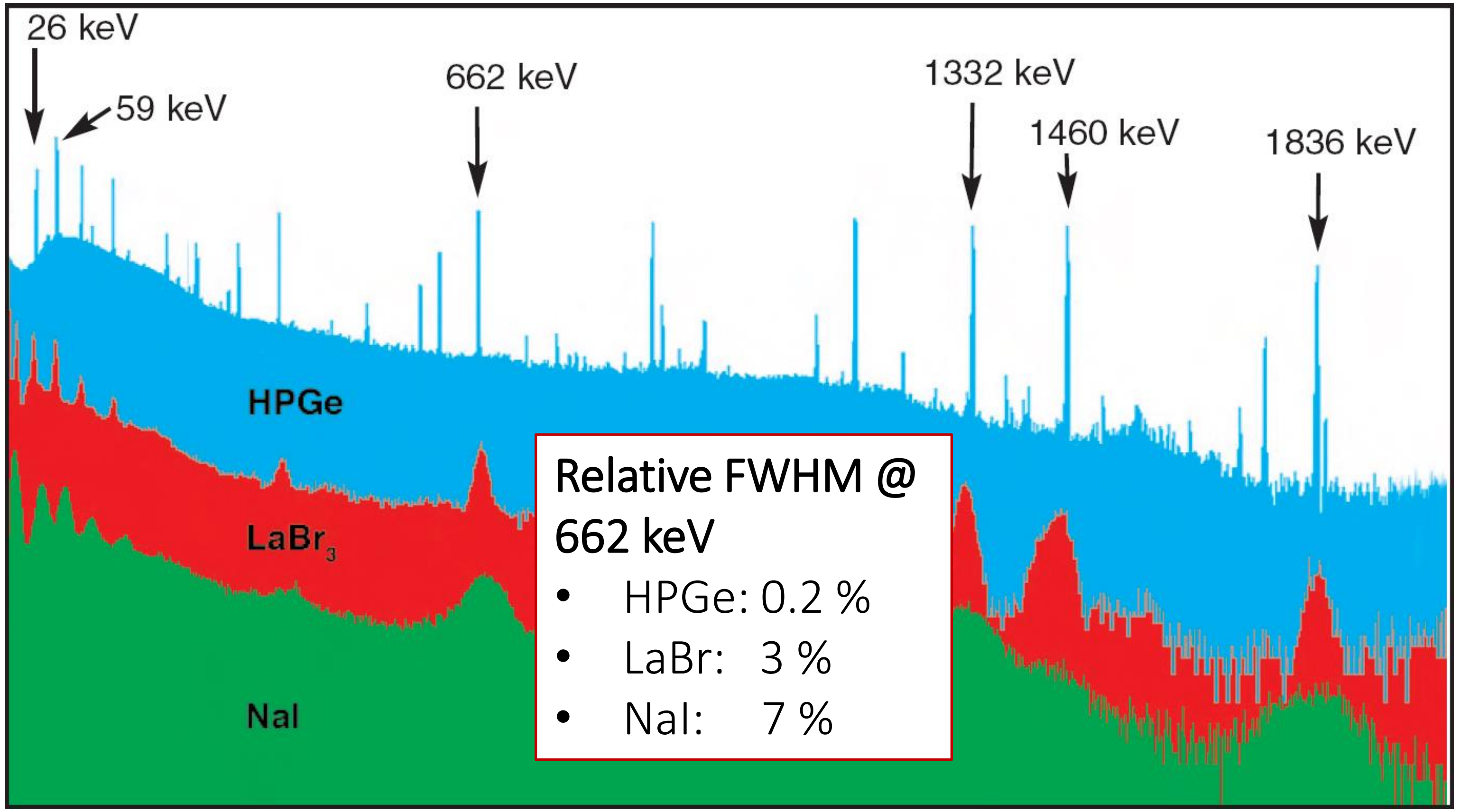
- The resolution ("sharpness") of a spectrum peak is usually measured by its Full Width at Half Maximum (FWHM)





- Peaks closer than 1xFWHM apart are often difficult to separate, even using software

Resolution comparison of different detector types



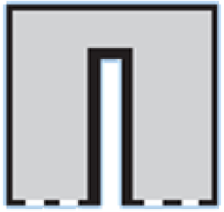
- For the remainder of the presentation, we will focus on HPGe detectors, as they are the most commonly used type of detector in the majority of Nordic laboratories.

The HPGe detector

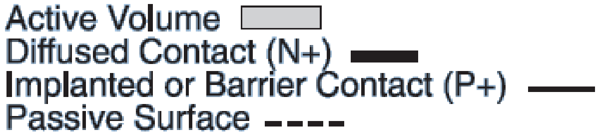
- The HPGe detector itself is basically a diode with a P-I-N structure connected to a FET
- The HPGe crystal is doped with impurity atoms (n+ or p+) to increase its conductivity
- HPGe detectors come in a variety of shapes and sizes with different efficiencies*

P-type coaxial detector

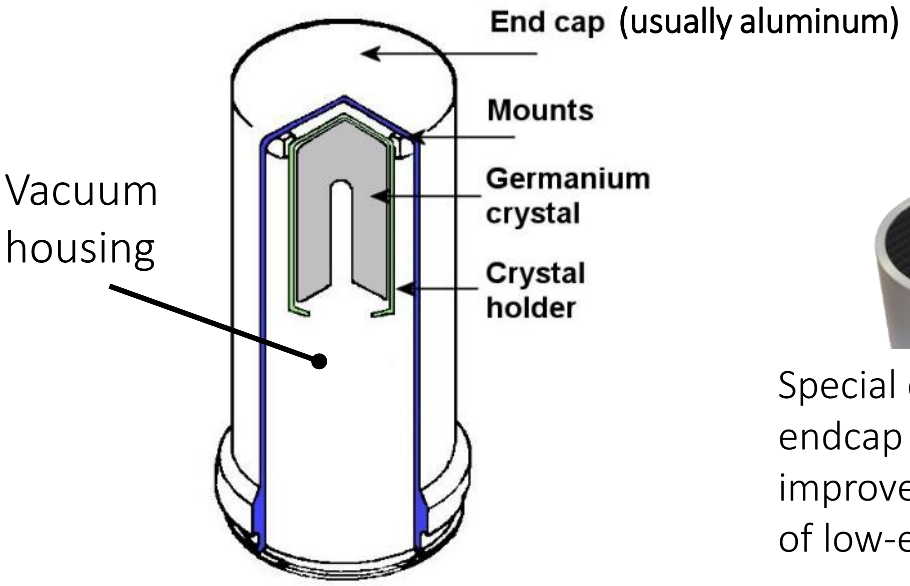
N-type coaxial detector



Well type detector



Planar detector



Special carbon fiber endcap window for improved transmission of low-energy photons

HPGe detector cooling

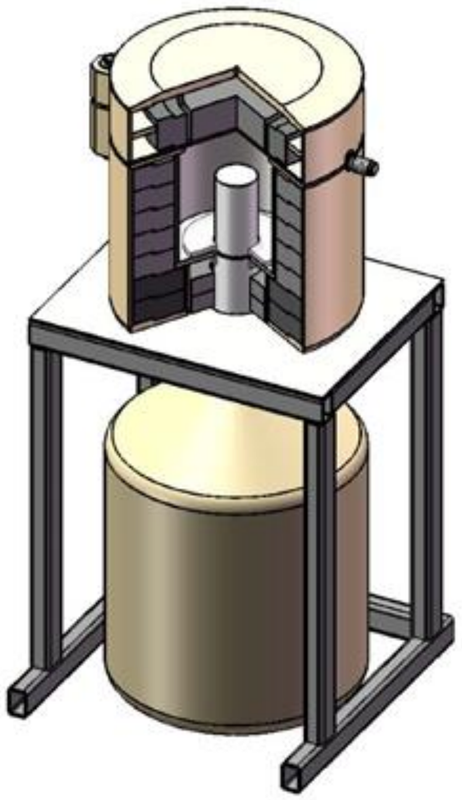
- HPGe detectors need to be cooled to cryogenic temperatures (< -170 °C) to function

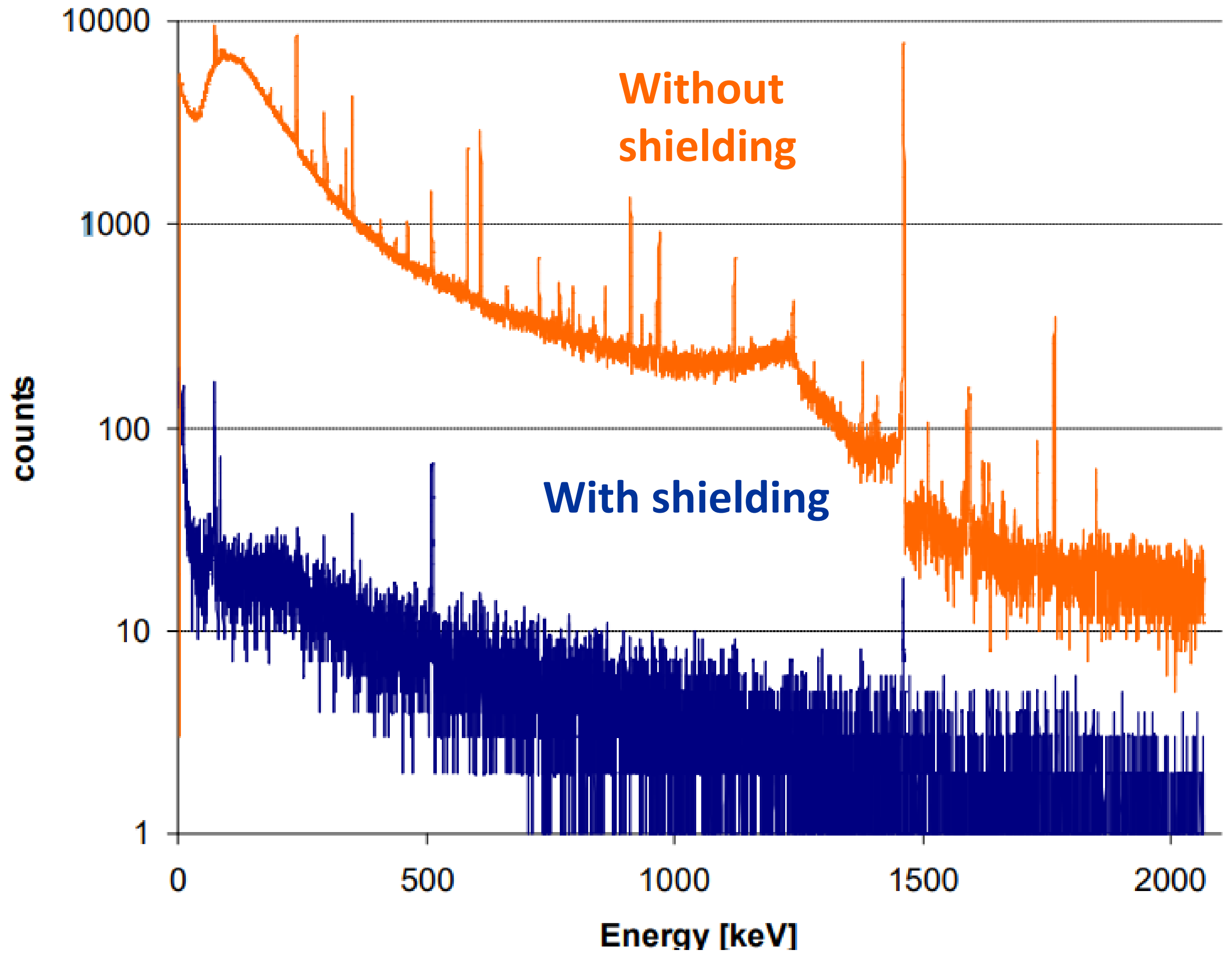
Liquid nitrogen cooling (-196 °C)

Electrical cooling

Hybrid cooling (recycles the liquid nitrogen)

Shielding the detector to reduce background

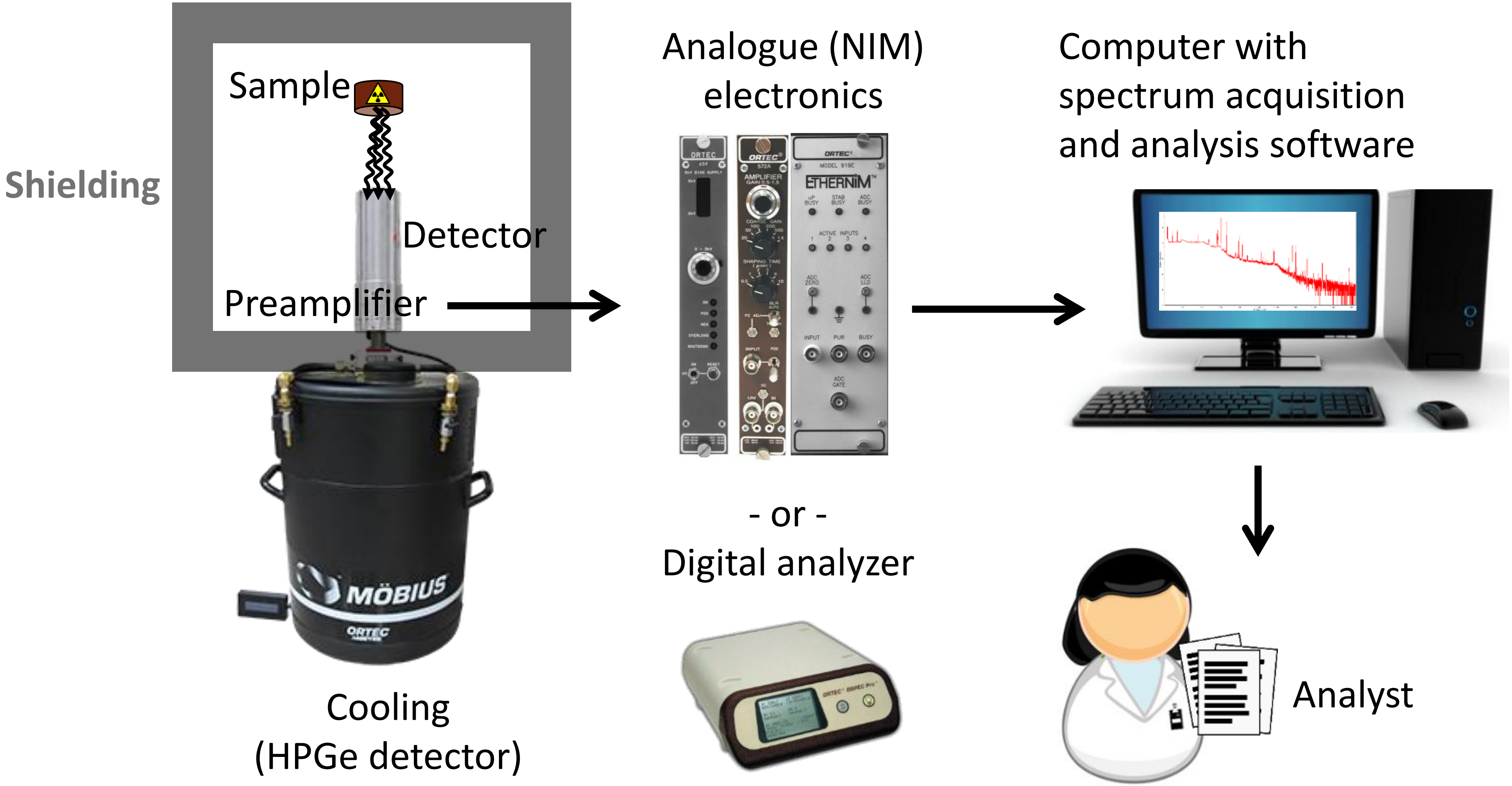




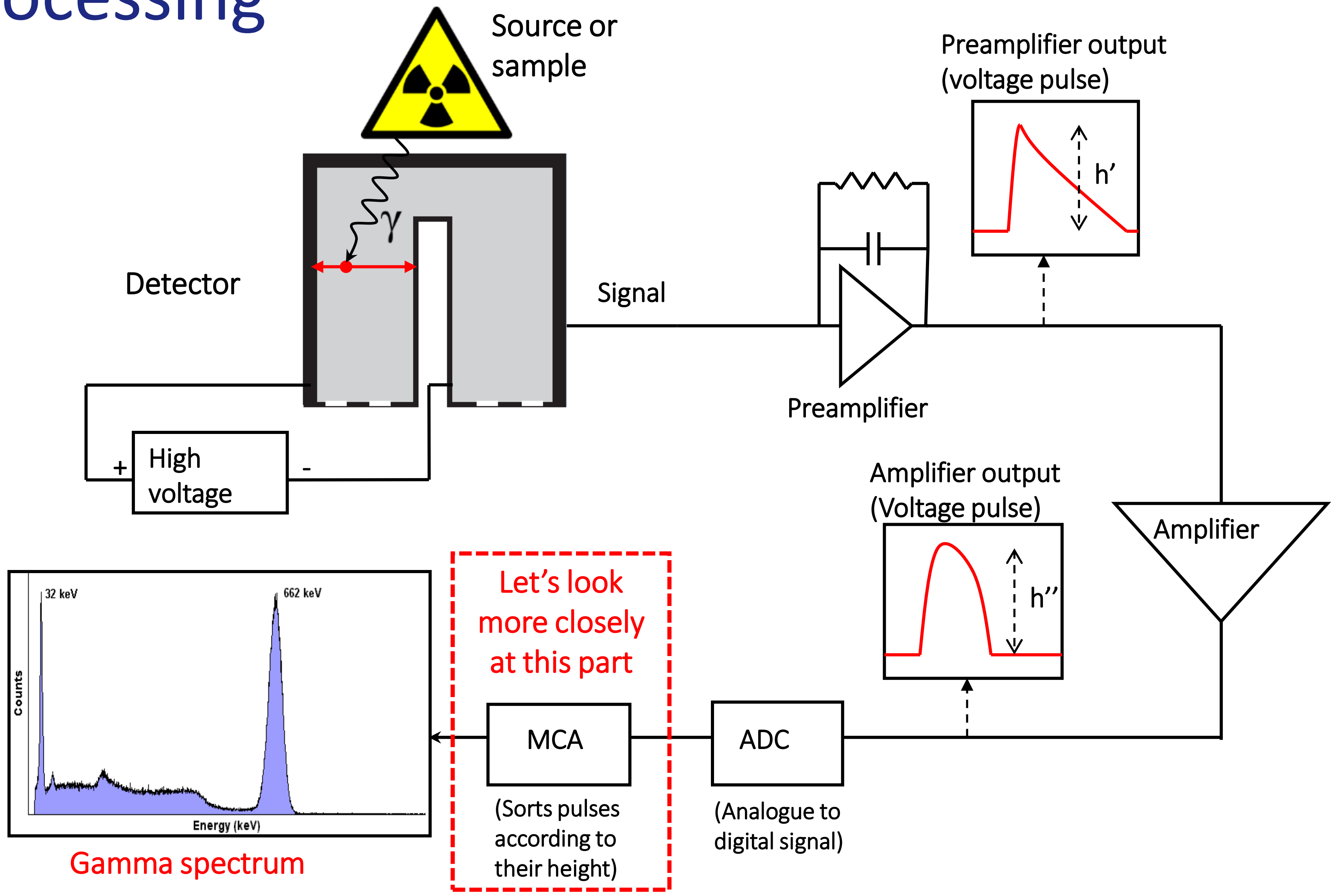
Agenda

01	What is gamma-ray spectrometry?
02	The origin of the gamma spectrum
03	Photon interaction mechanisms
04	Detector types for gamma spec.
05	**The complete measurement system**

Overview of the entire measurement system

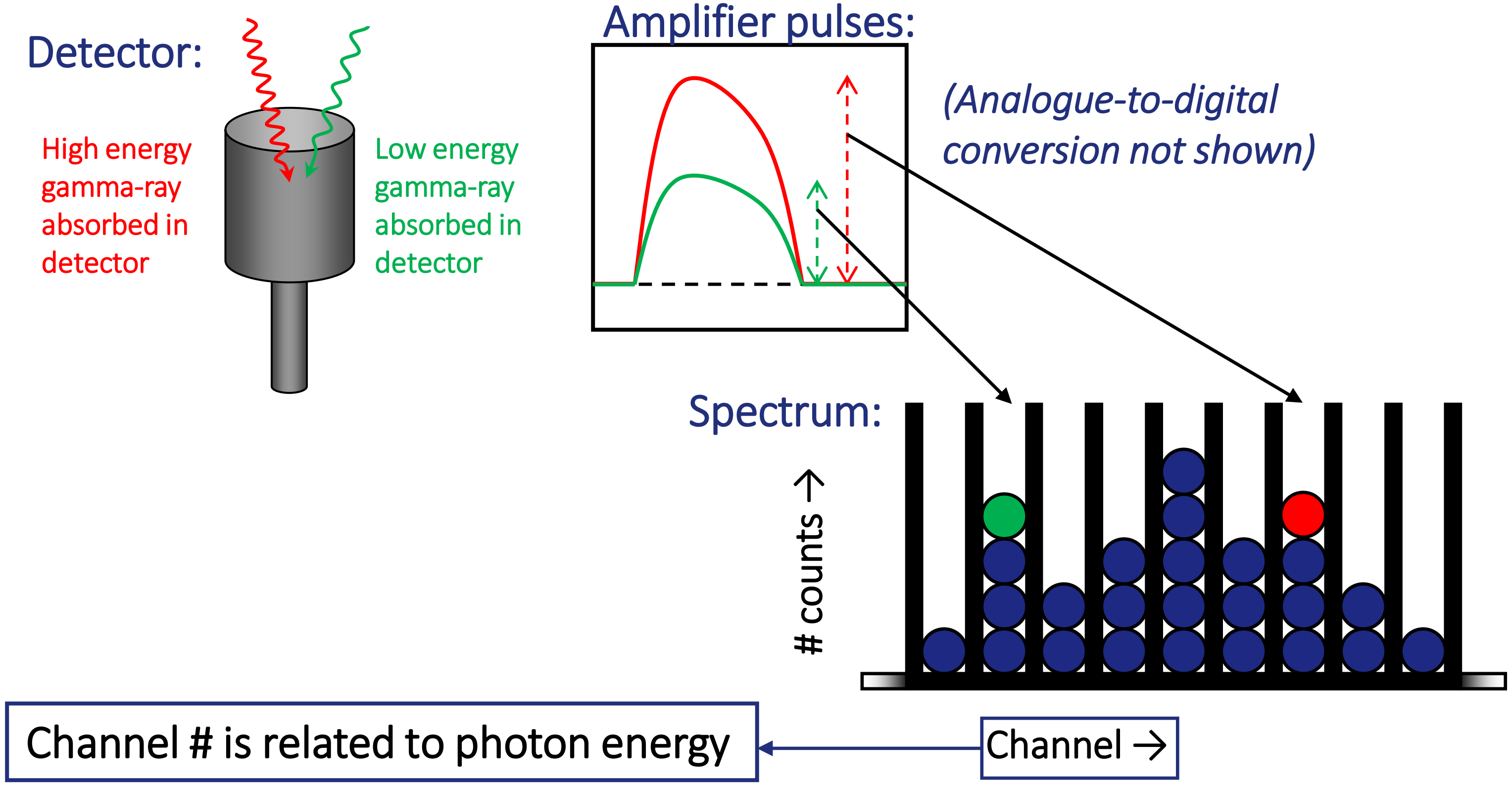


Signal processing



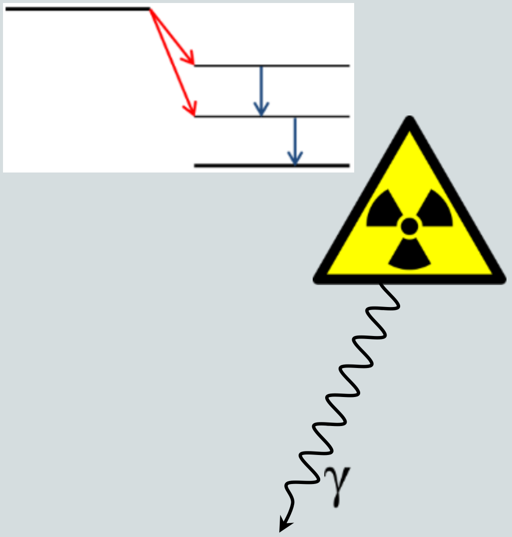
The multi-channel analyzer (MCA)

- The MCA sorts pulses from the amplifier into the spectrum according to their height



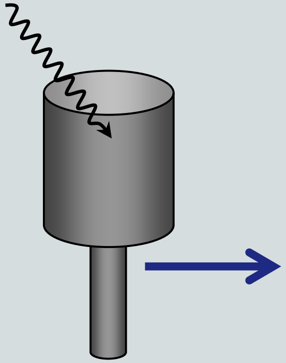
Summary of the basics

1.

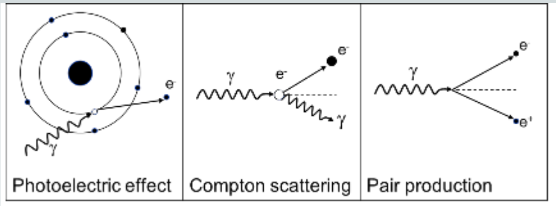


A gamma-ray emitting radionuclide sends out one or more gamma-rays with energies precisely defined by the radionuclide’s decay scheme.

2.

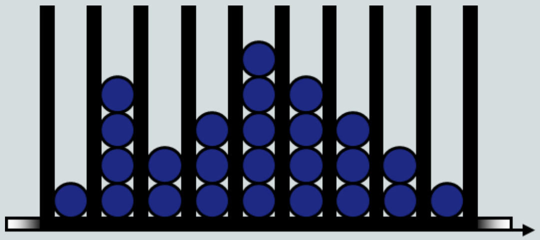


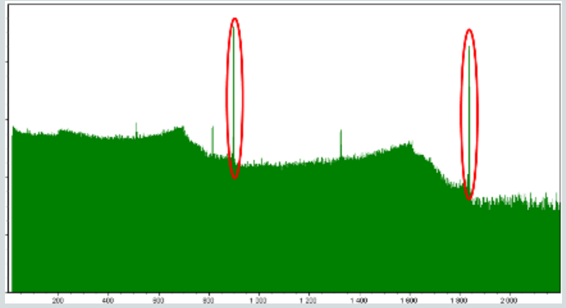
Signal processing / MCA



The gamma-ray interacts with a detector, depositing all or some of its energy there. The energy signal is processed through a measurement system.

3.





Each processed signal yields one "count" in the gamma spectrum. After many counts have been registered, characteristic full energy peaks appear.

4.

Nuclide	Activity [Bq/kg]
K-40	512 ± 29
Co-60	63 ± 6
Cs-134	104 ± 7
Cs-137	338 ± 11

With proper analysis, the gamma spectrum can be used to **identify** and **quantify** the activity of the radionuclide(s) measured by the detector.

Thank you for the attention!

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