Gamma Spectroscopy of Natural Radionuclides: techniques and instrumentation

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Carpathian Summer School, Sinaia - RO

Link to CAEN Educational

CAEN Edu introduction

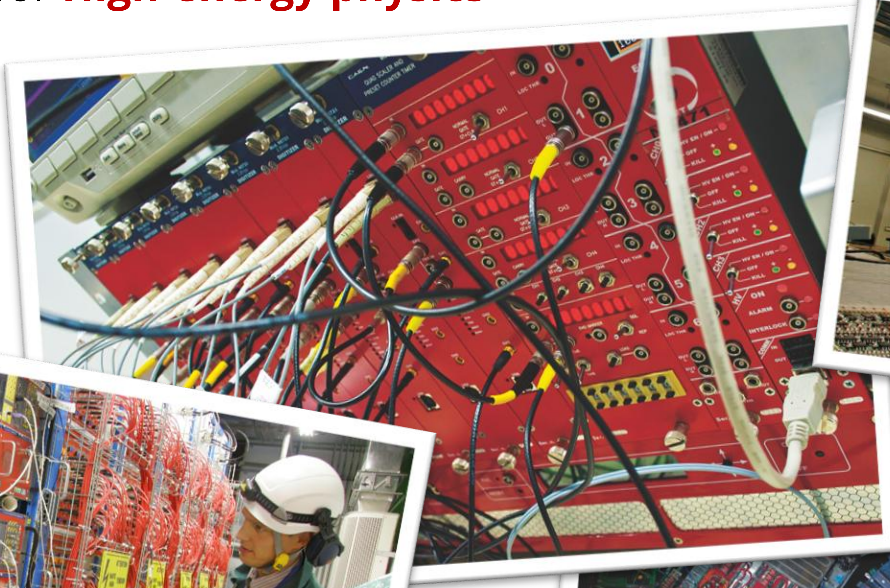
CAEN S.p.A. is an industrial spin-off of the Italian Institute of Nuclear Physics founded in 1979

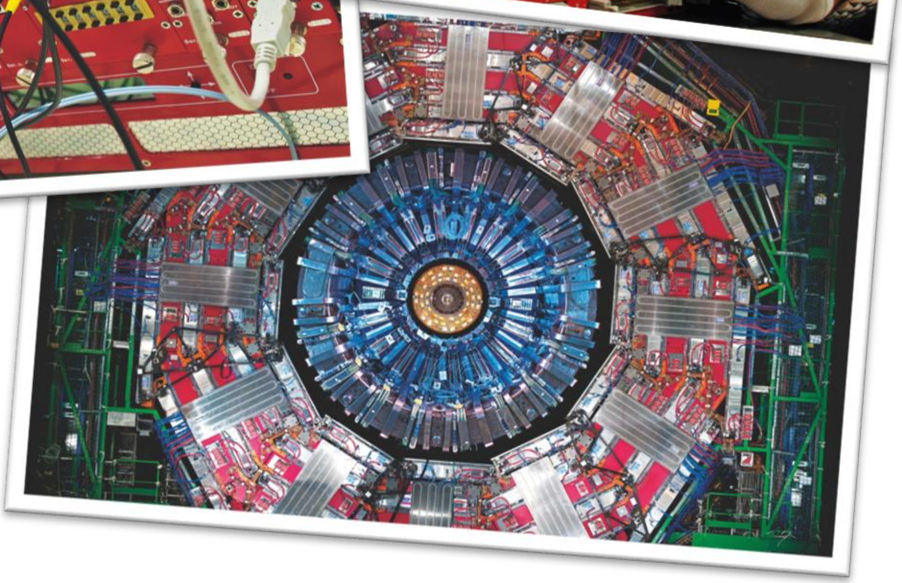
Core business: Electronic Instrumentation for **High-energy physics**

→ High Voltage and Digital Pulse Processing

- **HQ** in Italy
- **3** direct sales offices in U.S., Germany, India
- **30+** distributors worldwide
- **160+** specialized employees
- **5000+** customers

- *High Energy Physics*
- *Astrophysics*
- *Neutrino Physics*
- *Dark Matter Investigation*
- *Nuclear Physics*
- *Material Science*
- *Medical Applications*
- *Homeland Security*



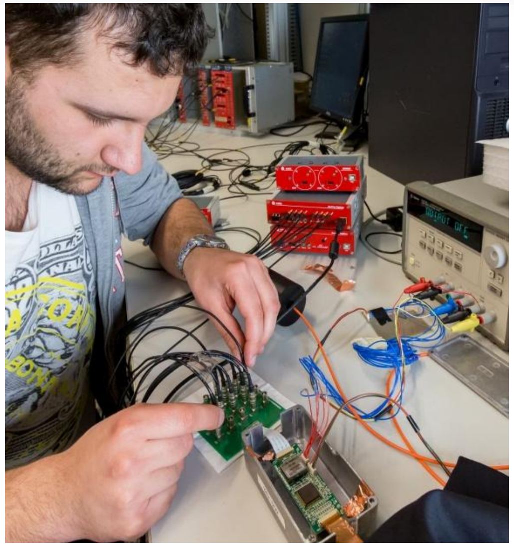


Modern physics experiments for Advanced Labs based on the latest technologies and methods

80+
Activities

14
Edu kits

50+
Institutions



Mission

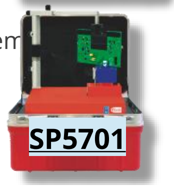
- Guide students towards the comprehension of different physics phenomena with experiments based on state-of-the art technologies, instruments and methods
- Target the experiment depending on the student educational level. From high school level (grade 11,12) up to undergraduate physics laboratory and PhD courses.

A lot of experiments

Nuclear Physics and Radioactivity

γ Spectroscopy
- ✓Detecting γ-Radiation
- ✓Poisson and Gaussian Distributions
- ✓Energy Resolution
- ✓System Calibration: Linearity and Resolution
- ✓A comparison of different scintillating crystals: Light Yield, Decay Time and resolution
- ✓γ-Radiation Absorption
- ✓Photonuclear cross-section/Compton Scattering cross-section

β-Radiation
- ✓ Response of a Plastic Scintillating Tile
- ✓β Spectroscopy
- ✓β-radiation: Transmission through Matter
- ✓β-Radiation as a Method to Measure Paper She and thin layer thickness



Nuclear Imaging - PET
- ✓Basic Measurements: γ Spectroscopy and System
- ✓Positron Annihilation Detection
- ✓Two-dimensional Reconstruction of Source
- ✓Spatial Resolution

γ Environmental Radioactivity (outdoor)
- ✓ Environmental monitoring in land field
- ✓ Ground Coverage Effect on the Environmental
- ✓ Human Body Radioactivity
- ✓ Environmental detection as a function of the s
- ✓ Radioactivity maps production
- ✓ Radiological evaluation of the building materia
- ✓ Geochemical and mineral exploration

γ Environmental Radioactivity (indoor)
- ✓Energy calibration of System based on LYSO crystal
- ✓Background Measurements
- ✓Fertilizer and photopeak identification
- ✓Identifications Sample Test
- ✓Soil sample identification
- ✓Samples Comparison
- ✓Radon passive measurements

GM Detectors
- ✓Statistics: Uncertainty as a function of live time
- ✓Environmental Background
- ✓Lead Shielding Effect on Environmental Radioactiv
- ✓Detecting Ionizing-Radiation
- ✓Samples Comparison

Particle Physics

Photons
- ✓Quantum Nature of Light
- ✓Hands-on Photon Counting Statistics

Cosmic Rays
- ✓Statistics
- ✓Muons Detection
- ✓Muons Spectrum
- ✓Muons Vertical Flux on Horizontal Detector
- ✓Zenith Dependence of Muons Flux
- ✓Random Coincidence
- ✓Detection Efficiency
- ✓Cosmic Flux as a function of the altitude
- ✓Cosmic Shower Detection
- ✓Environmental and Cosmic Radiation
- ✓Absorption Measurements
- ✓Solar Activity Monitoring

Particle Detector Characterization

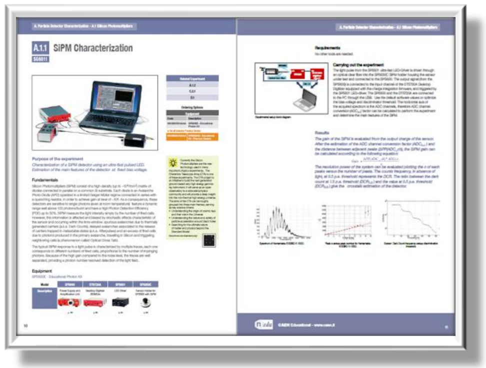
Silicon Photomultiplier (SiPM)
- ✓SiPM Characterization
- ✓Dependence of the SiPM Properties on the bias vo
- ✓Temperature Effects on SiPM Properties

Photomultiplier Tube (PMT)
- ✓ Measurement of Photomultiplier Plateau Curves

Pulse Processing: Open FPGA

- ✓Analog signal acquisition and waveform Visualizatio
- ✓Waveform digitizer with leading edge trigger...........

Short Guide



Main Topics:

- *Experiment task*
- *Short description*
- *Equipment list*
- *Requirements*
- *Quick guide*
- *Experimental results*

Detailed Guide

Guide Topics:

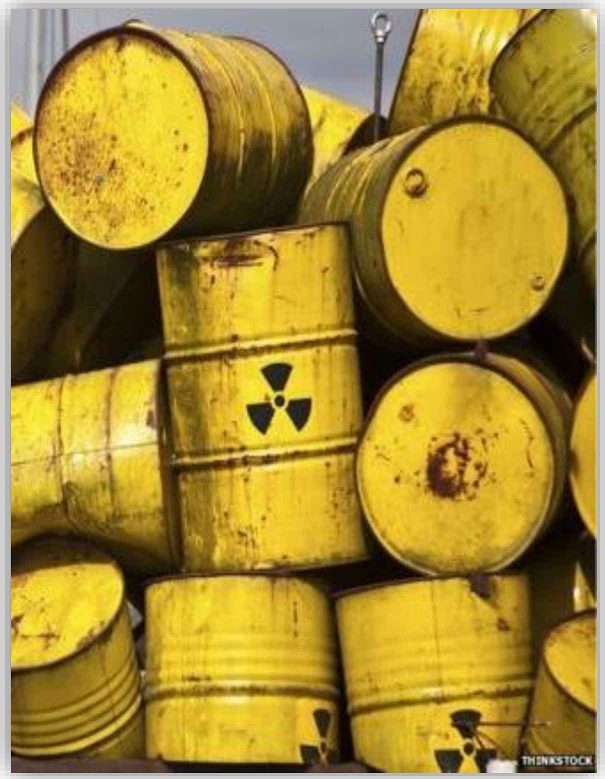
- *General Information*
- *Introduction*
- *Physics Pills*
- *Required Equipment*
- *Getting Started*
- *Experimental Procedure*
- *Results*
- *Links related to this topic*

Theory
(just 10 minutes ☺)

Commonly the concept of Radioactivity is always associated with a dangerous feeling!

Nuclear Wars

Nuclear accidents

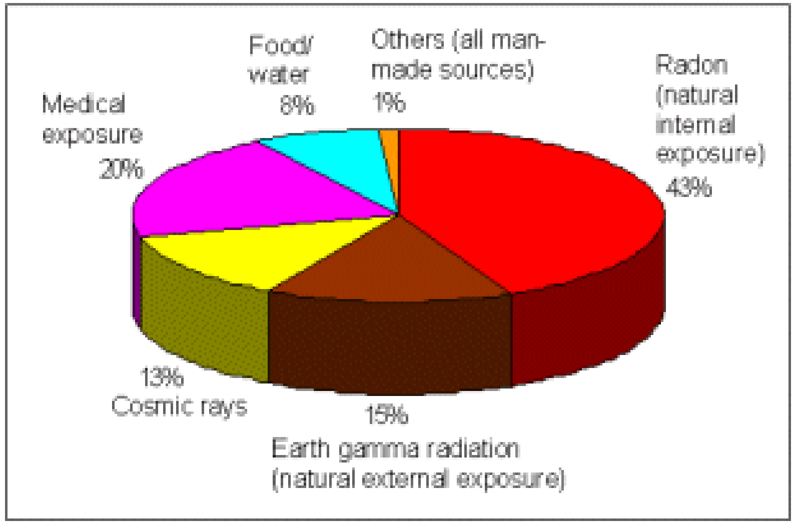


Radioactive Waste

Radiation is a natural part of our environment!

Radioactive sources:

- ***Natural***: **NORM** (Naturally Occurring Radioactive Material), soil, water, air and food contribute to our exposure to ionizing radiation
- ***Cosmic rays***
- ***Industrial***: nuclear elements produced by industry
- ***Medical***: nuclear medicine



https://www.who.int/ionizing_radiation/env/en/

Radioisotope types

Natural radionuclides [mean abundance]:

- ^{40}K [2-2.5] %
- $^{238,235}U$ [2-2.5] ppm
- ^{232}Th [8 -12] ppm
- All has an half life $T_{1/2}$ > than the age of the solar system

Cosmic rays

Muons -> The intensity depends on the altitude and direction (N/S vs E/W)

Radionuclides from cosmic rays

- ^{14}C, ^{7}Be, ^{3}He

Energy Distribution in Cosmic Rays
W. G. Pollard
*Phys. Rev. **44**, 703 – Published 1 November 1933*

Artificial radionuclides

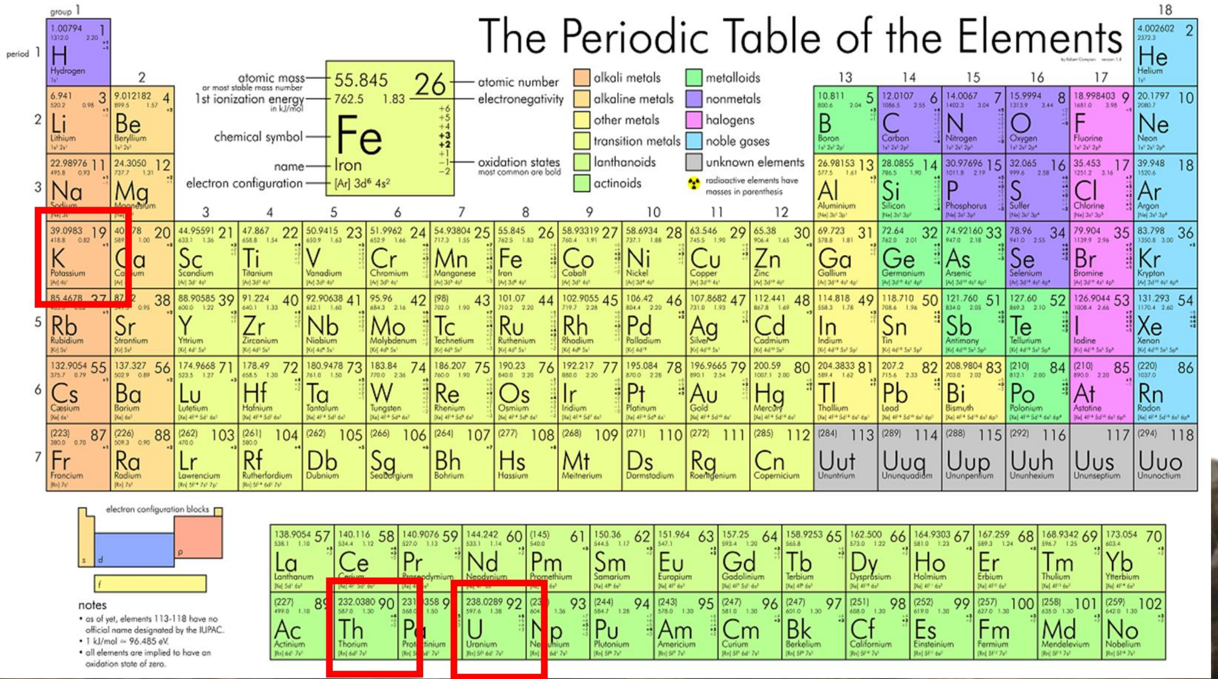
- From bombs or Nuclear power plants (ex. ^{137}Cs, actinides)
- Industrial (^{133m}Xe, ^{133}Ba, ^{241}Am) and medical (^{19}F, ^{67}Ga) radioistopes

Natural gamma emitters

During the creation of the Earth, most of the elements initially produced were radioactive and they have been decayed to more stable forms.

The original radioactive elements still present on Earth are those that have a halftime comparable to the Earth. They are responsible for environmental radioactivity and internal warming of the planet and originate from elements very heavy without stable isotopes.

They mostly decay through the α and β channels



Element	Radioisotopes	Isotopic Adundance	Half time	Tipycal Adundance
Potassium	^{40}K	0.012%	1.3 × 10^9 years	0.02 g/g [2%]
Uranium	^{238}U	99.3 %	4.5 × 10^9 years	2-3 μg/g [ppm]
Thorium	^{232}Th	100 %	14.1 × 10^9 years	8-12 μg/g [ppm]

Not all nuclei are stable…

Most of the matter nuclei are stable even when they undergo chemical reactions

Some nuclei, however, are unstable (radionuclides): they transform spontaneously and reach stability by emitting radiation.

This process is called **radioactive decay**!

Nuclear decay is a random event… like popcorn popping!

Elements and Activity

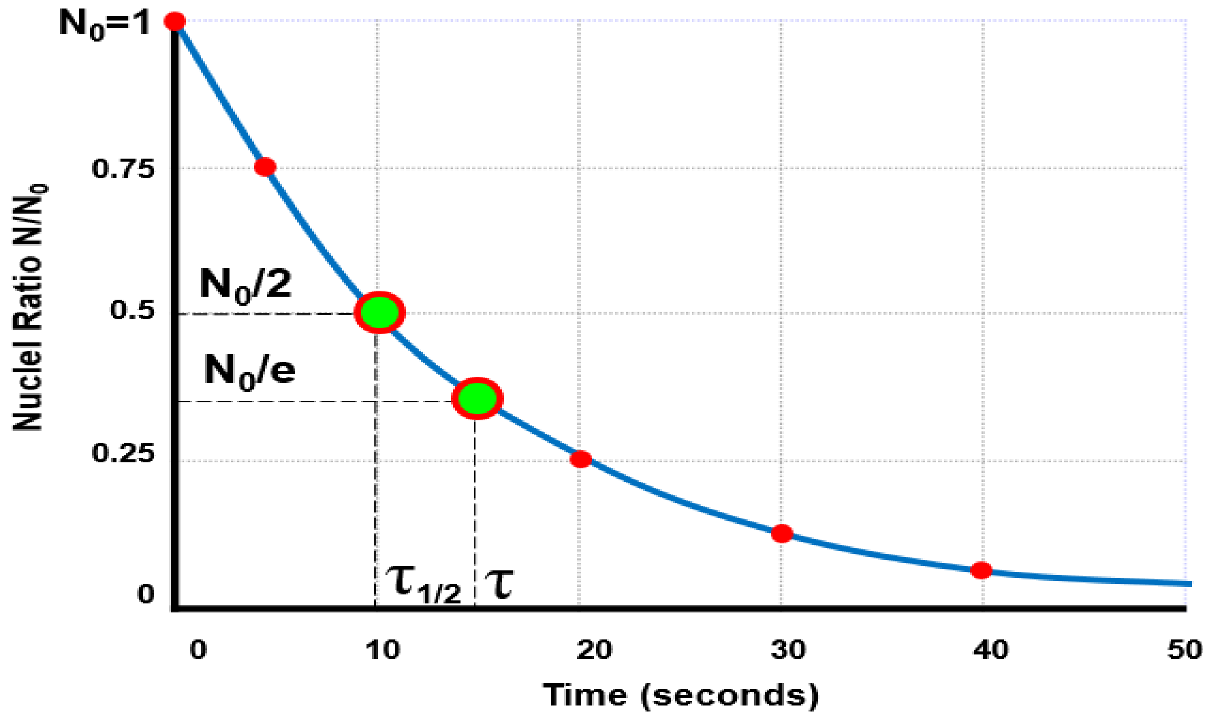
$^{A}_{Z}X$ X = Element symbol Z = Atomic Number (number of protons) N = Neutronic number (number of neutrons)

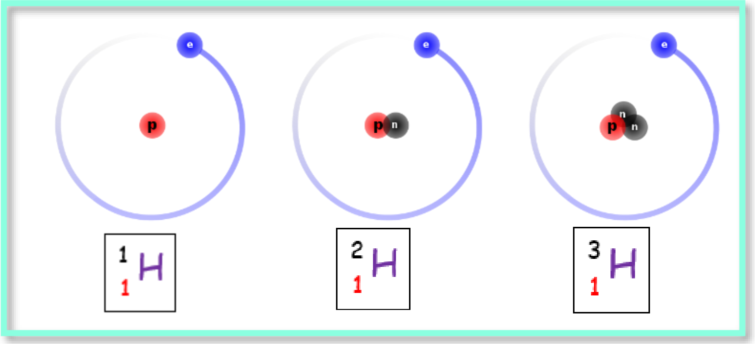
A = Mass Number (Z + N)

Isotopes

Elements with the same atomic number and different mass number

Ex: Hydrogen isotopes





The **activity** is defined as the number of decay per second. The international system unit is the Bequerel [Bq]

It is an exponential law:

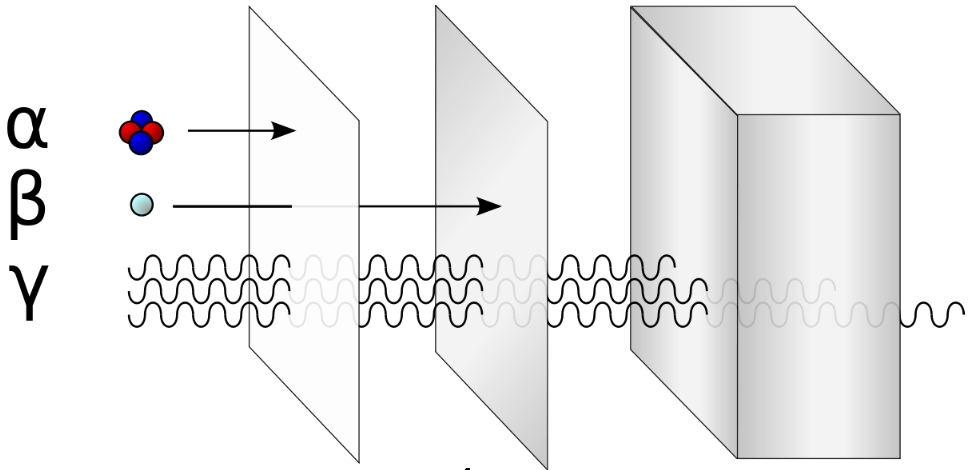
$$N(t) = N_0 e^{-\lambda t}$$

Where:

- λ is the ***decay constant*** of the nuclide
- ***Mean time*** *of the element:* $\tau = 1/\lambda$
- ***Half life***: $t_{1/2} = \tau \lg 2 \approx 0{,}7\tau$

The radioactive decay is a physics phenomena happening when an instable nucleus reaches a new state of equilibrium emitting particle or radiation

Type	Mass	Q	Description
α	6.68 10^{-27} Kg	+2	${}^{4}_{2}He$
β	0.9 10^{-30} Kg	-1	Electron (e^-)
γ	0	0	Electromagnetic radiation (photon)



- In the ***α and β decays***, the nucleus is transformed into a different type emitting alpha or beta particles

$$ {}^{238}_{92}U \rightarrow \alpha + {}^{234}_{90}Th $$

$$ {}^{234}_{90}Th \rightarrow \beta + {}^{234}_{91}Pa $$

- In the ***γ decay***, the nuclide emits photons to go to a lower energy and more stable state. The photon energy corresponds to the excess of energy between the two states

$$ X^* \rightarrow X + \gamma $$

Usually, the gamma decay is generated after an alpha or a beta decay which generate excited states. The excited states goes to a more stable state emitting photons and without changing state

Radioactive decays

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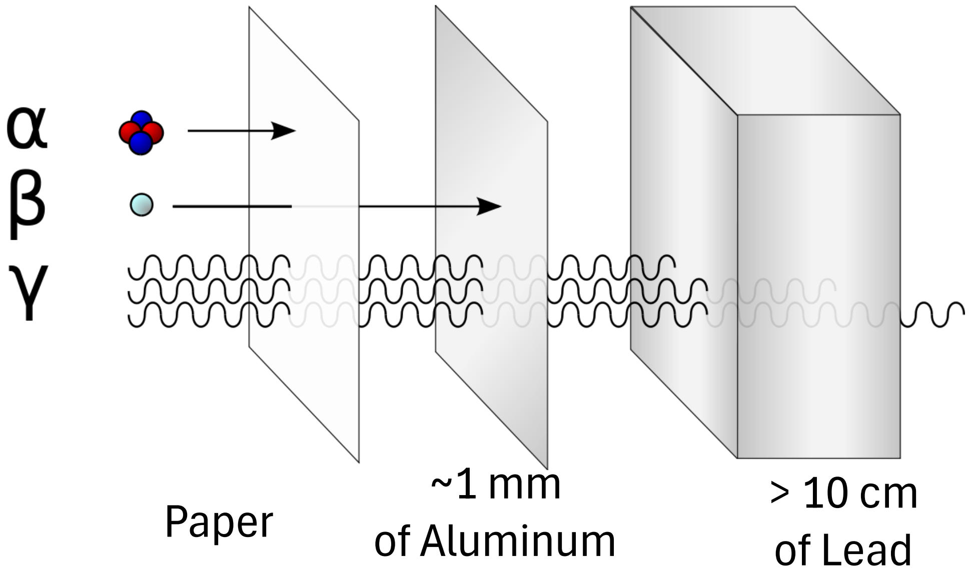

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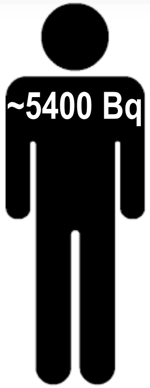
Natural radioisotopes are primarily gamma emitters

Usually, ... decay is generated after an alpha or a beta decay which generate excited states. The excited states goes to a more stable state emitting photons and without changing state

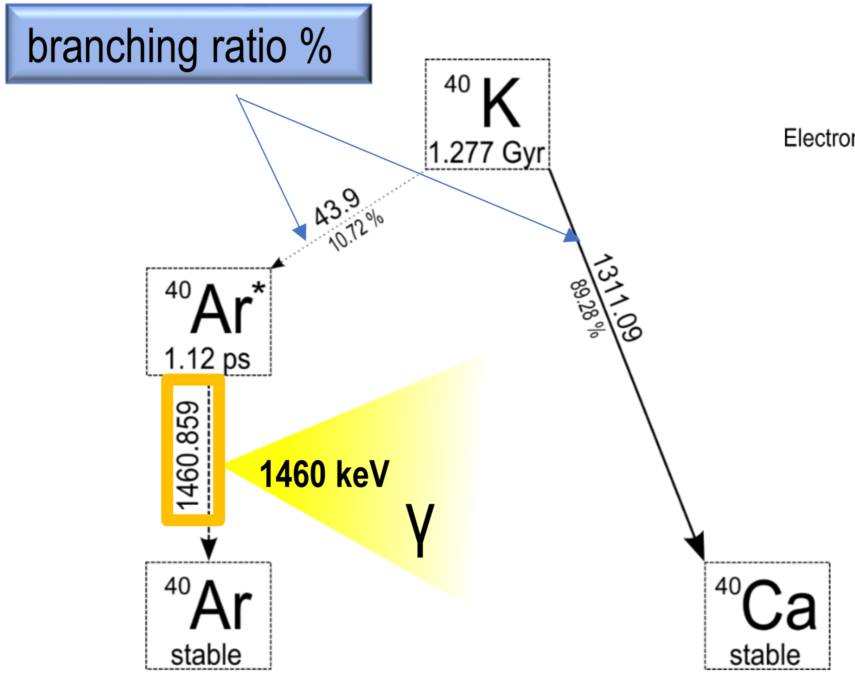
Potassium 40

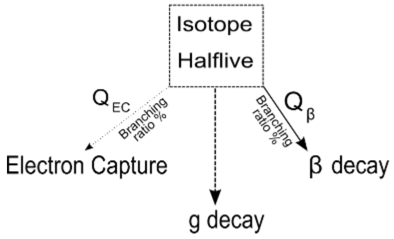


Potassium is essential for living. In the human body, most of the potassium is stored in the muscles. Potassium is also present in the soil, building materials, plants, animals and it is used in fertilizers.
In nature exists 3 potassium isotopes:

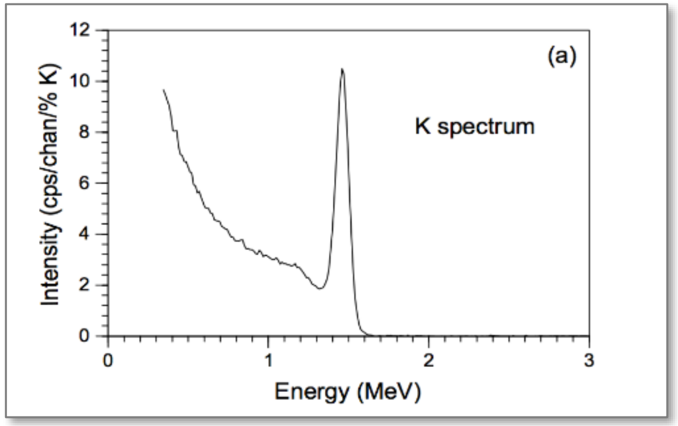
Type	^{39}K	^{40}K	^{41}K
n° protons	19	19	19
n° neutrons	20	**21**	**19**
Abundance (%)	93.26	0.01	6.73
$t_{1/2}$	Stable	1.3 10^9 y	stable

Considering a hundred thousand potassium atoms, only 12 are actually radioactive!



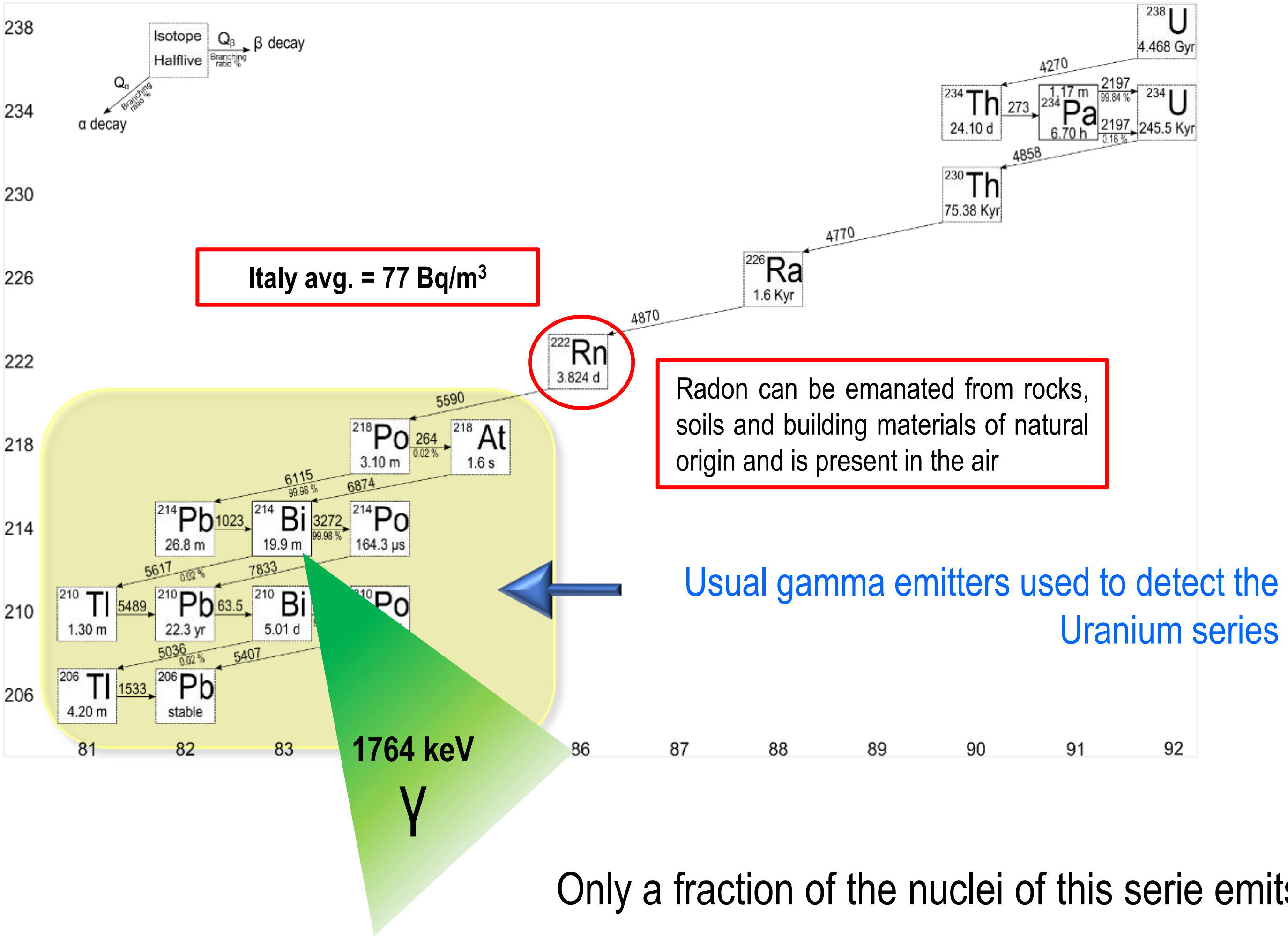


^{40}Ar decays emitting a gamma of 1460 keV (10%)
Measurement % -> 1% = 313 Bq/kg



Uranium 238

The ^{238}U is the most common isotopes of the uranium element with a relative abundance of 99% and an half life of about 4,5 billions of years. The decay chain of an element down to its foundamental state is also called **radioactive series.**



- All the decay products found in the chain have a shorter average life in comparison to the generating elements of the series.
- The **secular equilibrium** is the situation when the quantity of an isotope remains constant having the same production and decay rate. This equilibrium is usually broken when one of the sons is a gas that goes away.

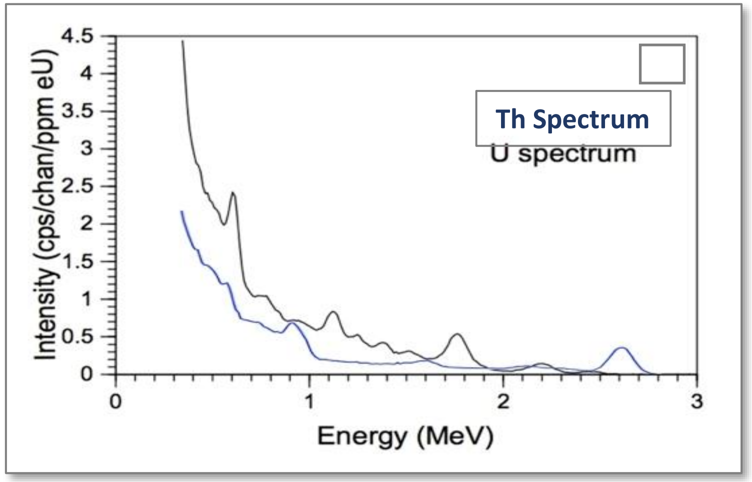
14 transformations are needed for the ^{238}U to be transformed into the stable ^{206}Pb

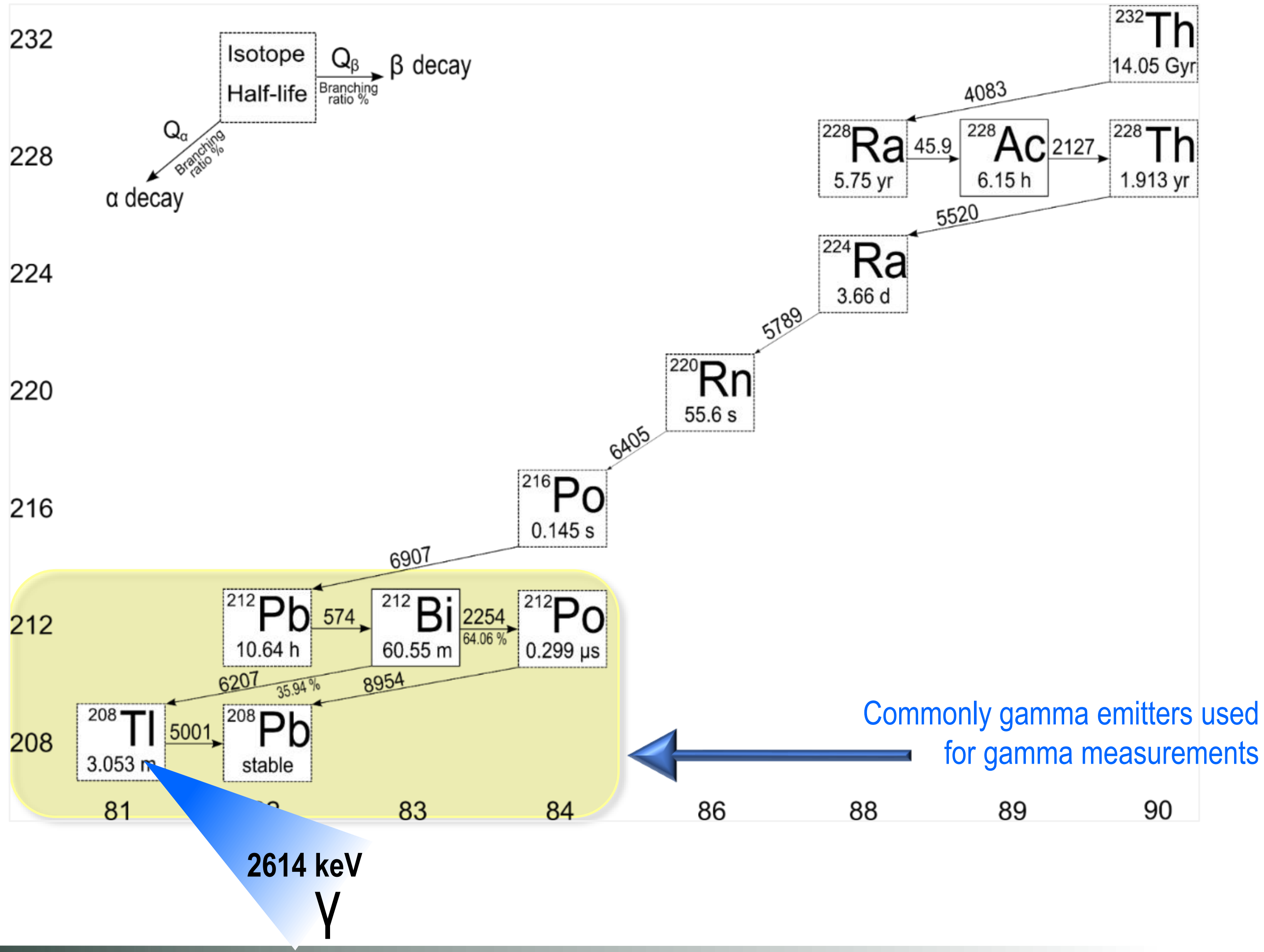
Only a fraction of the nuclei of this serie emits gamma radiation!

Thorium 232

^{232}Th has 142 neutrons, is the most stabel isotopes of the thorium family (10^{10} years) and represents almost all thorium existing in nature.

- It decays slowly with alpha decay on ^{198}Ra. The thorium serie finishes with a stable element: the ^{208}Pb. This serie contains the following elements: astatine, bismuth, lead, polonium, radium and radon
- The quantity of thorium in the Earth is 3 or 4 times larger than uranium. It can be extracted from monazite sands or as a sub-product of rare Earth elements extraction



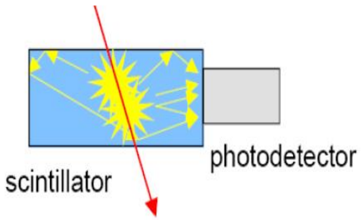


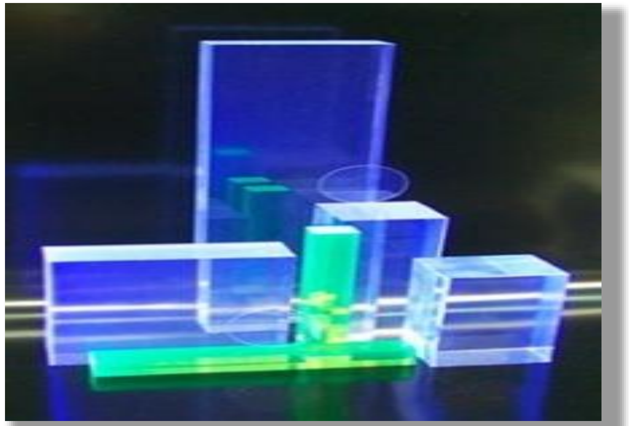
Instrumentation and measurements

GammaEDU Description - Scintillator

Energy deposition by an ionizing particle:

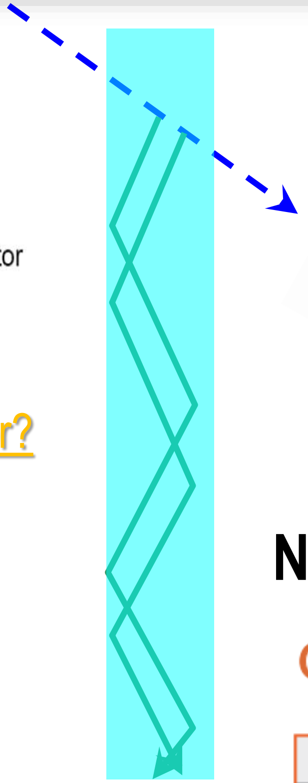
- Generation of light
- Transmission of scintillation light
- Detection





What are scintillators used for?

- To measure the energy released
- To measure the passage time of radiation



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

NaI(Tl)

General Properties

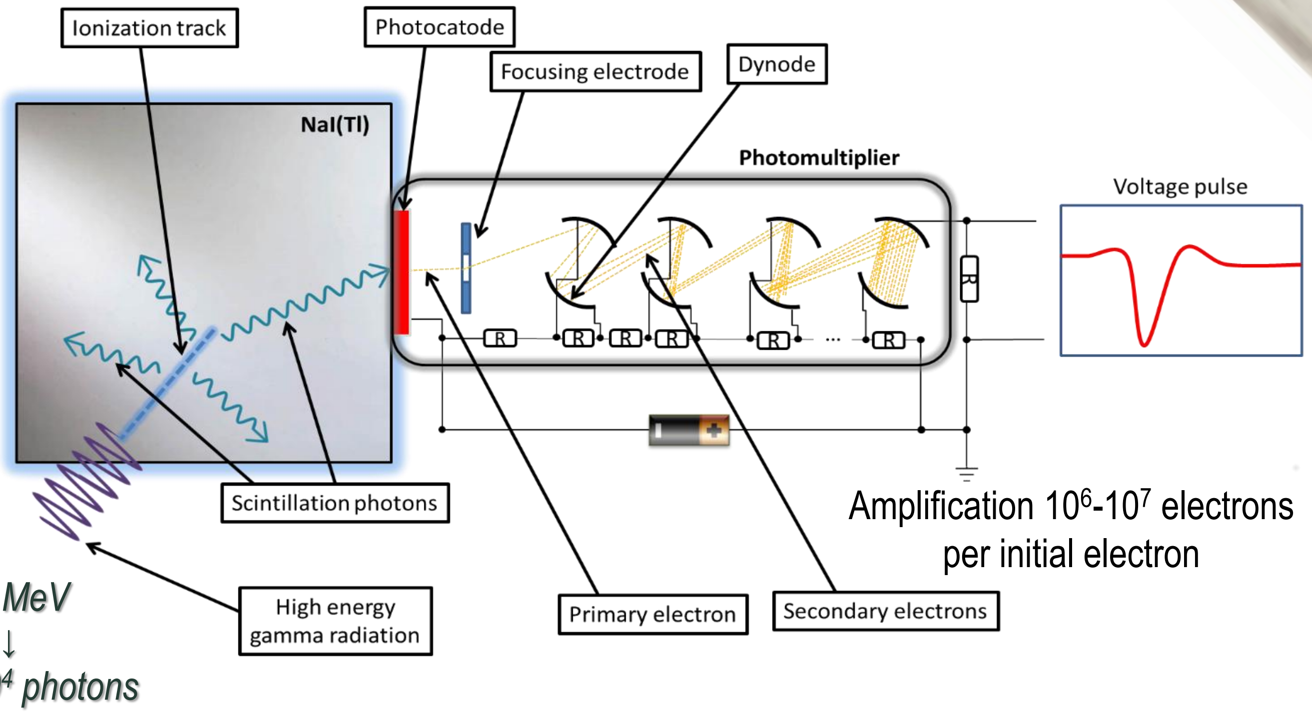
Density(g/cm^3)	3.67
Melting point(K)	924
Wavelength of emission peak(nm)	415
Light output(Photons/Mev)	40,000
Decay time(ns)	264
Cleavage plane	(100)
Hygroscopic	Yes
Refractive index	1.85
Hardness(Mho)	2

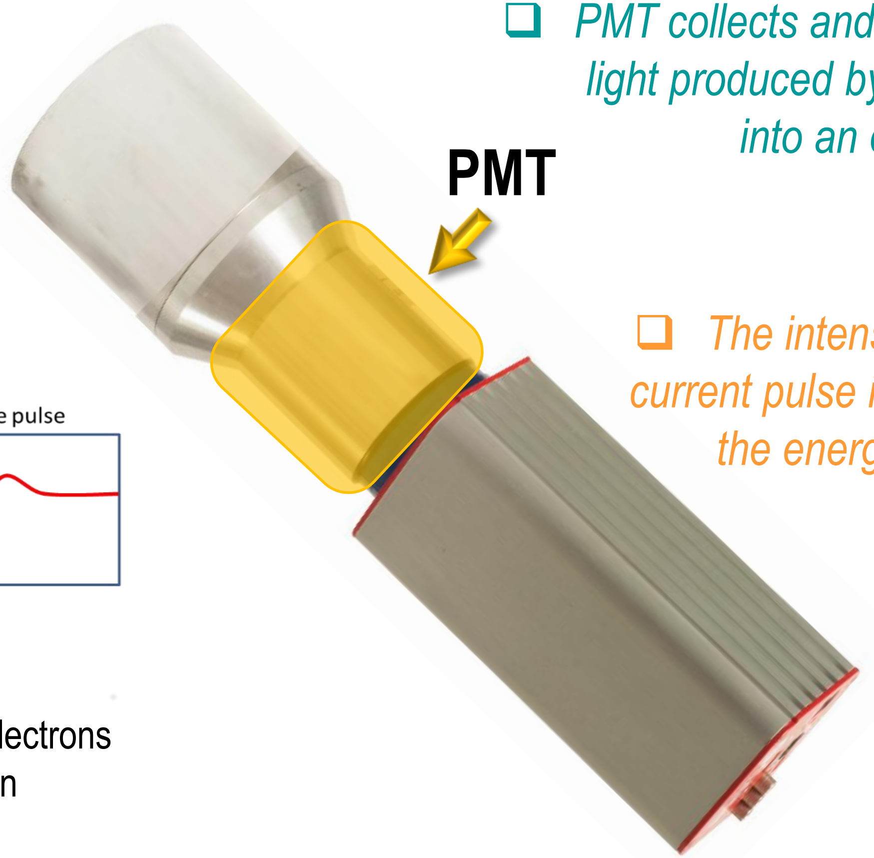
Inorganic (crystalline structure)
Up to 40000 photons per MeV
High Z
Large variety of Z and ρ
Un-doped and doped
ns to μs decay times
Expensive

Organic (plastics or liquid solutions)
Up to 10000 photons per MeV
Low Z
ρ~1g/cm^3
Doped, choice of emission wavelength
ns decay times
Relatively inexpensive

Photodetector → From photons to electric current!

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





- *PMT collects and transforms the light produced by the scintillator into an electrical signal*
- *The intensity of the output current pulse is proportional to the energy of the incident photon!*

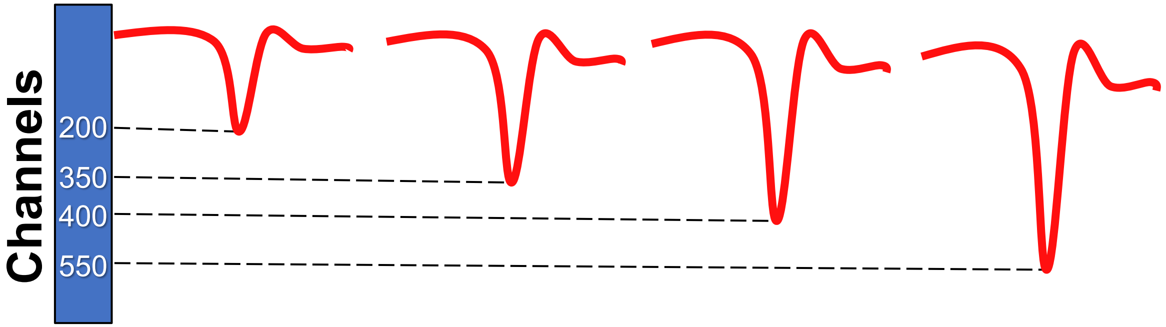
GammaEDU Description – *γ stream*

CAEN Gamma *stream* [S2580] is a compact and portable system for gamma ray spectroscopy with scintillation detectors, which provides an active **Multi-Channel Analyzer** (MCA) integrated in a 14-pin photo-multiplier tube (PMT) base.

Gamma *stream* fully integrates in a stand-alone device the high voltage to bias the PMT, the preamplifier to shape the signal from detector, and the MCA for a complete Pulse Height Analysis online.

Gamma *stream* makes easy the measurements with scintillation detectors **NaI(Tl)** [0.3l] with no need of additional cables.

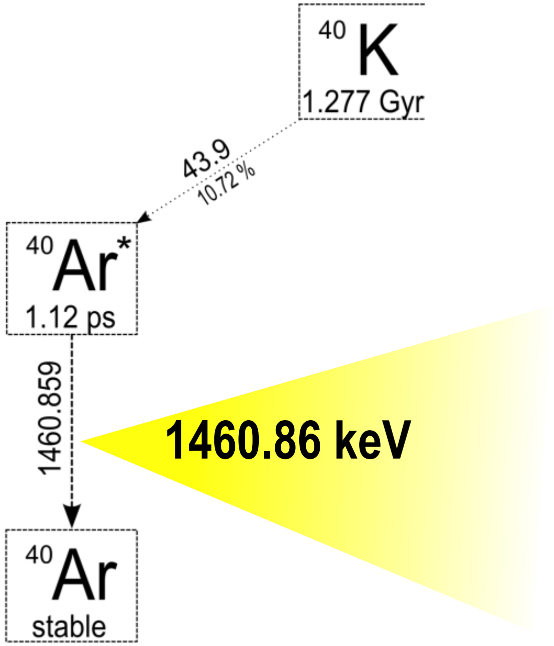
- High Voltage Power Supply (0 ÷ +1500V/500 μA)
- Charge Sensitive Preamplifier
- digital Multi-Channel Analyzer (12-bit and 62.5 MHz ADC) for scintillation spectroscopy
- Specialized for NaI(Tl), LaBr3(Ce), and CeBr3 with standard 14-pin and 10-8 stages PMTs
- Full stand-alone operation with embedded CPU, data storage (SSD) unit, and power supply for up to 6÷8 hours operation
- Wired and wireless connectivity via USB, Ethernet, Wifi and Bluetooth
- Acquisition modes: PHA, PHA with time stamp, Signal Inspector

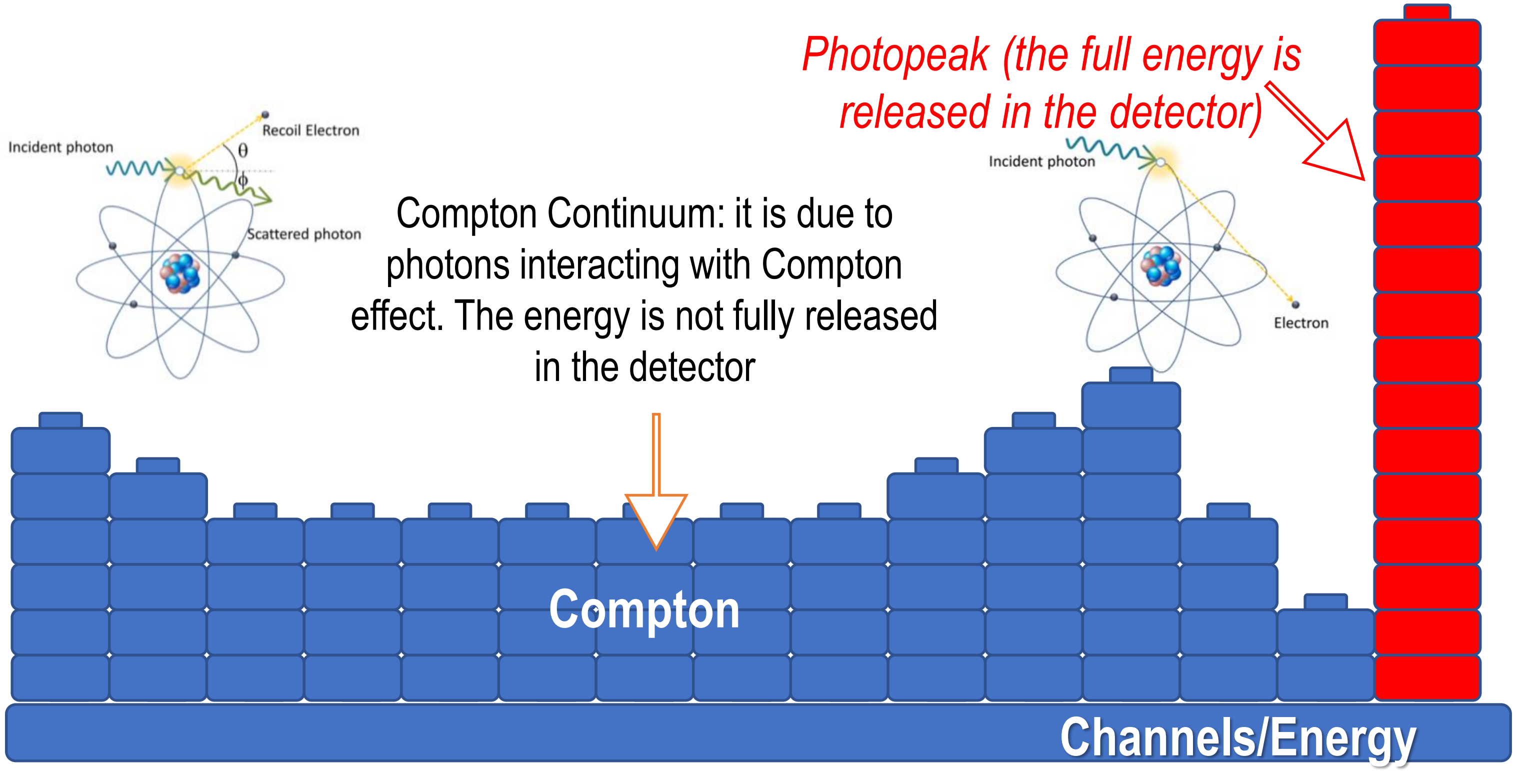


The acquisition channel is proportional to the energy of the incident photons!

The MultiChannel Analyzer MCA classifies input pulses base on their height 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. Since these output pulses are proportional to the energies of the incident radiation, the ADC can be used combined to a MultiChannel Analyzer (MCA) to generate energy distributions (spectra) of radioactive samples.

Ex. Monochromatic photons beam





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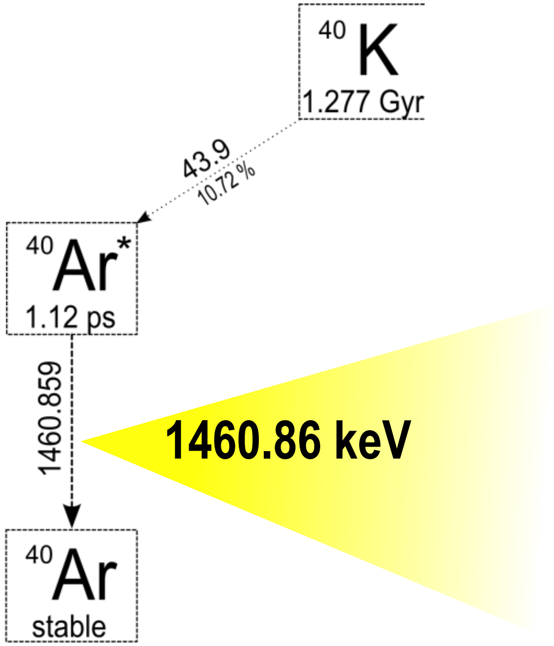

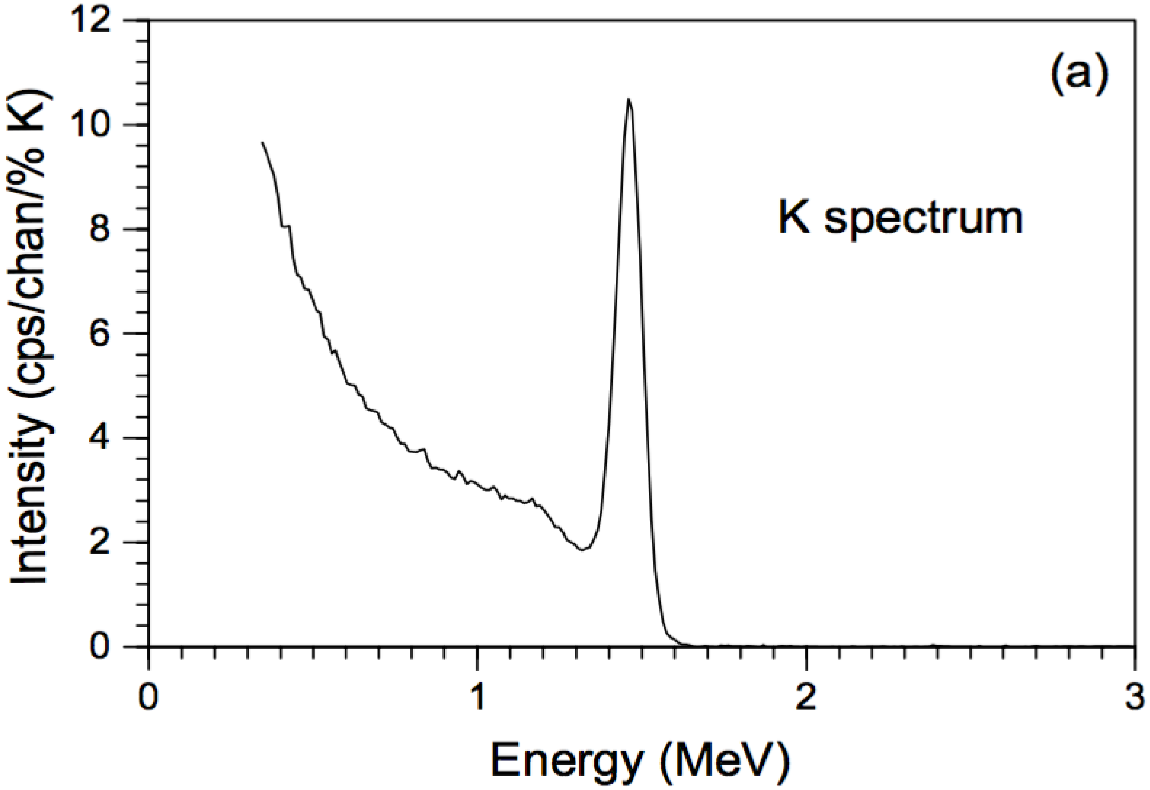

Energy Spectrum

The MultiChannel Analyzer MCA classifies input pulses base on their height saving them in a memory and are associated to an ADC. The output of every channel can be visualized in a pulse amplitude spectra.
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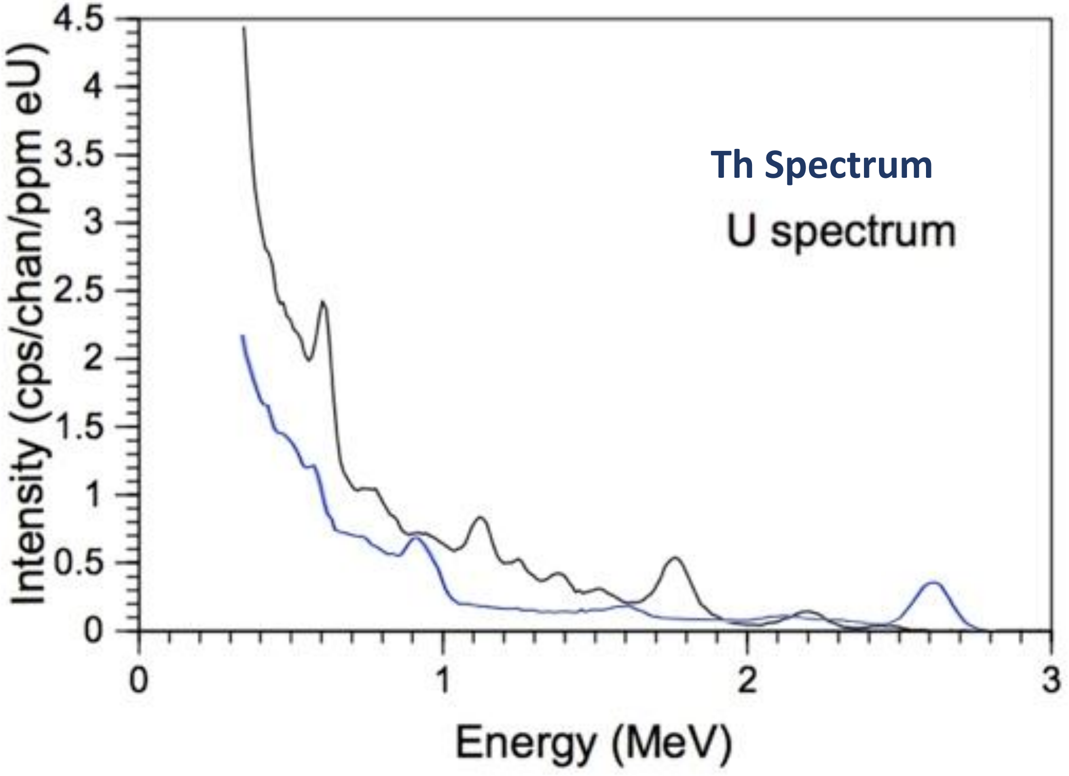
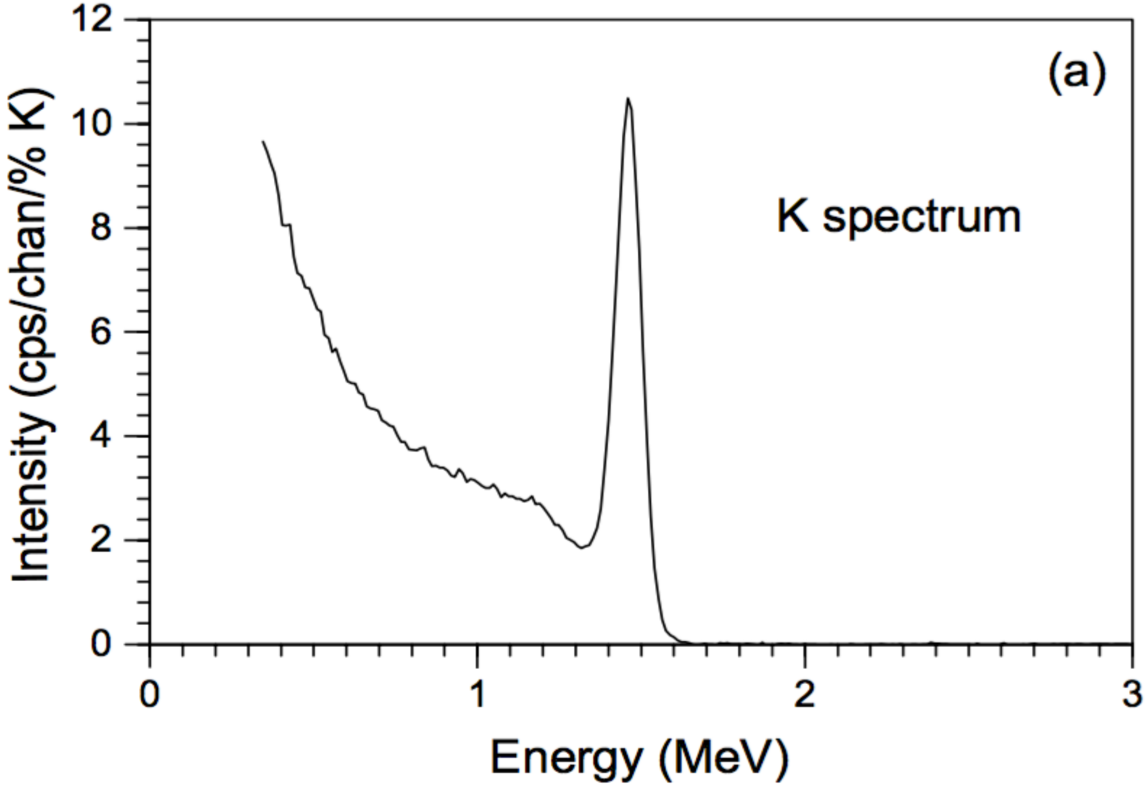
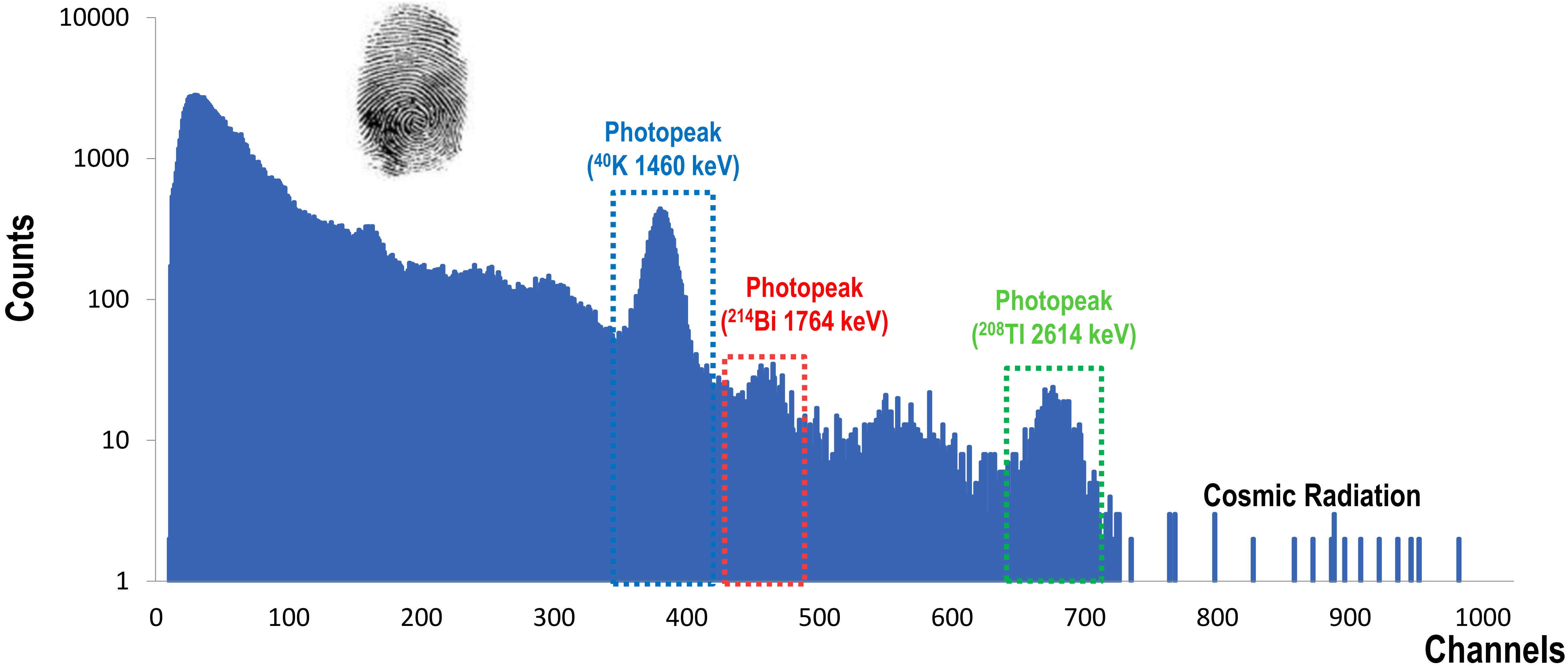




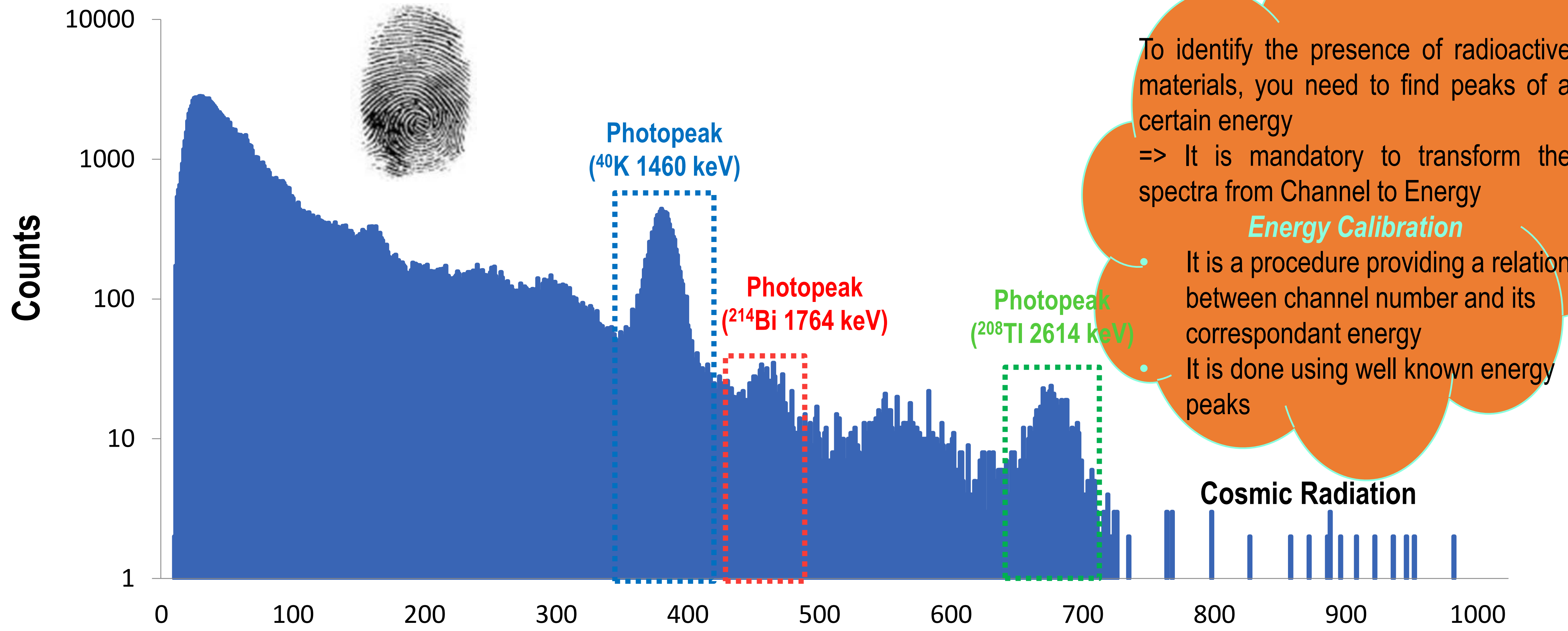
Typical Gamma Spectra

The photopeaks characterize the gamma spectrum. Each photopeak corresponds to the photons collected by the detector with an energy value equal to the emission ones. These photons release all their energy into detector.



Typical Gamma Spectra

The photopeaks charatcterize the gamma spectrum. Each photopeak corresponds to the photons coming into detector with an energy value equal to the emission ones. These photons release all their energy into detector.



To identify the presence of radioactive materials, you need to find peaks of a certain energy

=> It is mandatory to transform the spectra from Channel to Energy

Energy Calibration

- It is a procedure providing a relation between channel number and its correspondant energy
- It is done using well known energy peaks

In the energy range of the environmental measurements the calibration in energy corresponds to a linear transformation

=> Knowing the energy of 2 peaks it is possible to extract the equation of the line from 2 points

$^{40}K \Rightarrow E_K = 1460\ keV$

$^{208}Tl \Rightarrow E_{Th} = 2614\ keV$

^{208}Tl is coming from the radioactive chain of the ^{232}Th and is the highest energy gamma from natural sources

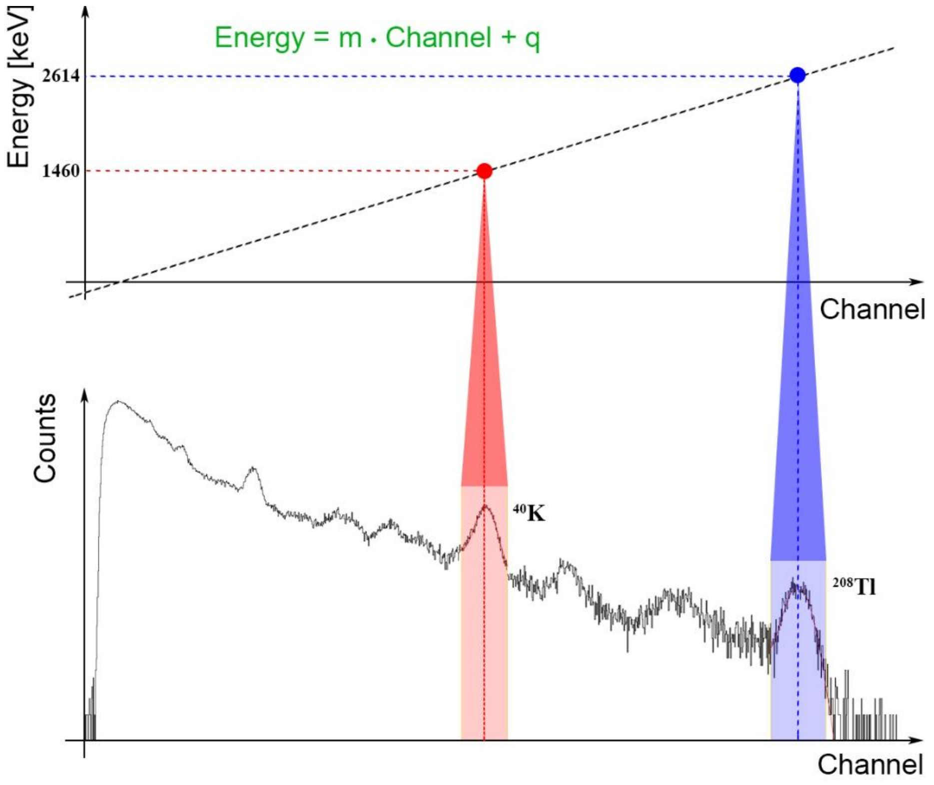
$A = (E_{Th}, Ch_{Th})$

$B = (E_K, Ch_K)$

$$\frac{Ch - Ch_K}{Ch_{th} - Ch_k} = \frac{E - E_k}{E_{th} - E_k}$$

$$\frac{Ch - Ch_K}{Ch_{th} - Ch_k} = \frac{E - 1460\ keV}{(2614 - 1460)keV}$$

Multichannel Calibration

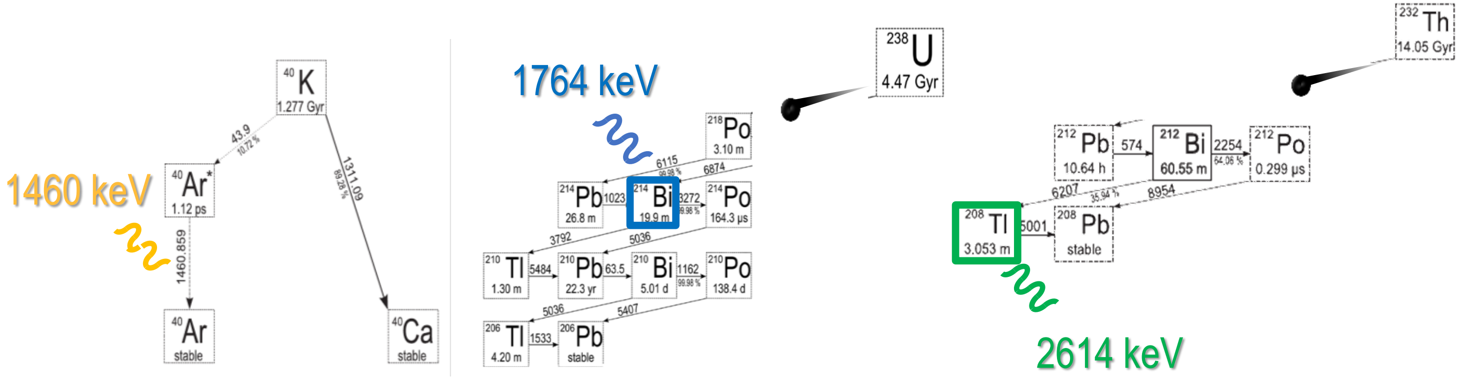


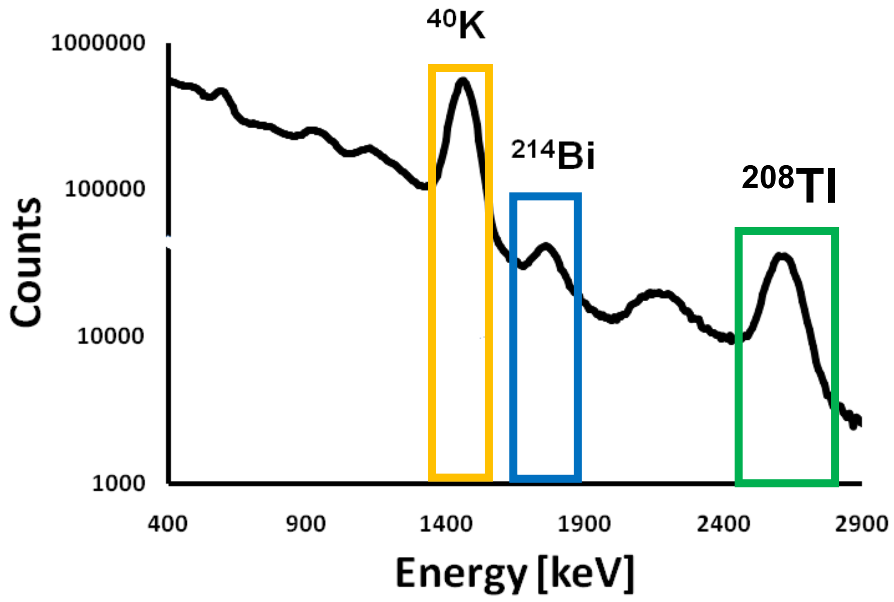
ROI Definition

Definition of the **Region(s) of Interest (ROI)** of the energy spectra. These windows are used to define the photopeak regions required to calculate the correspodant areas (integral of the ROI).

NOTE: *In every ROI there are different contribution effects (photopeak, compton continuum, background continuum, etc…)!*

Window	Isotope	Photopeak Energy (keV)	ROI (keV)
Potassio	^{40}K	1460	1370-1570
Uranio	^{214}Bi	1765	1660-1860
Torio	^{208}Tl	2614	2410-2810

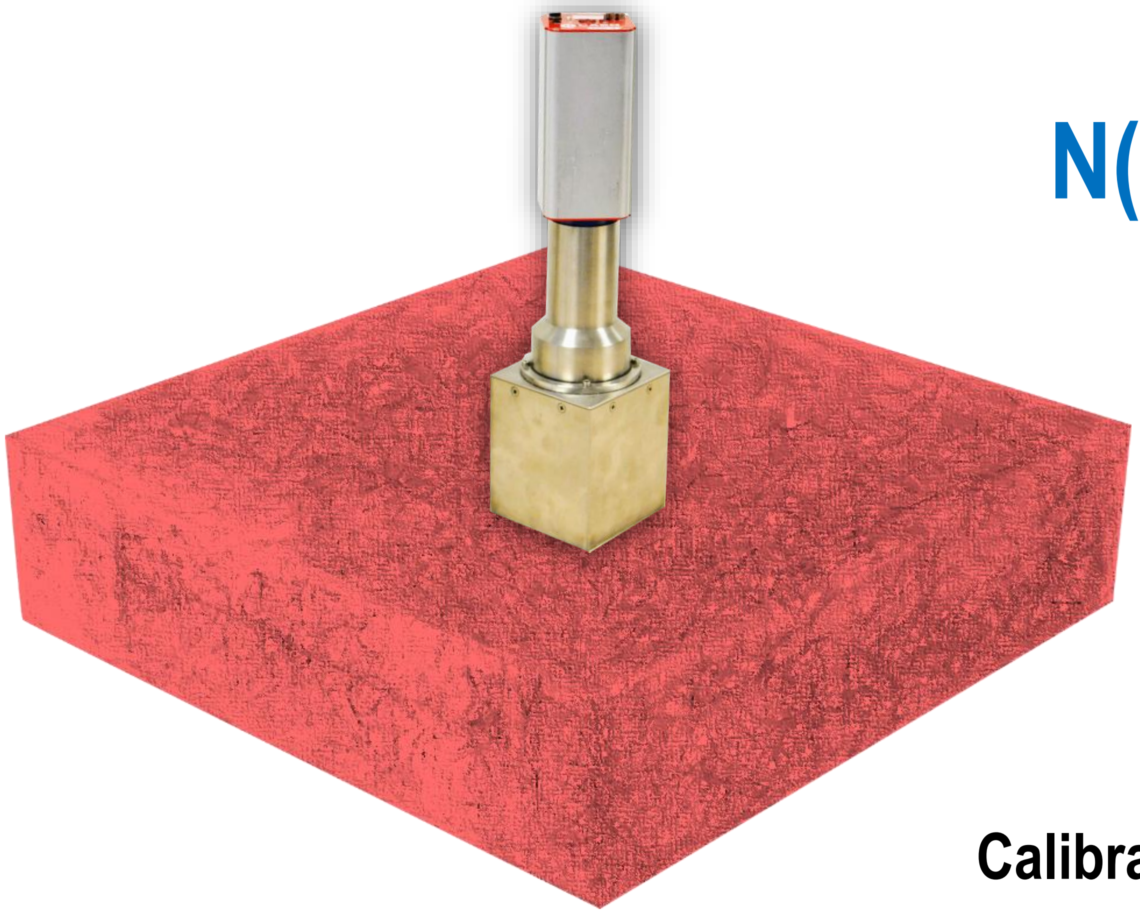




Count rate: number of counts per unit of time

$$n_i[cps] = \frac{N_i[conteggi]}{T[s]}$$

Calibration: from counts to the abundancies



$$N(cps) = A \cdot S$$

$$S = A^{-1} \cdot N$$

S is the sensitivity coefficient of the detector

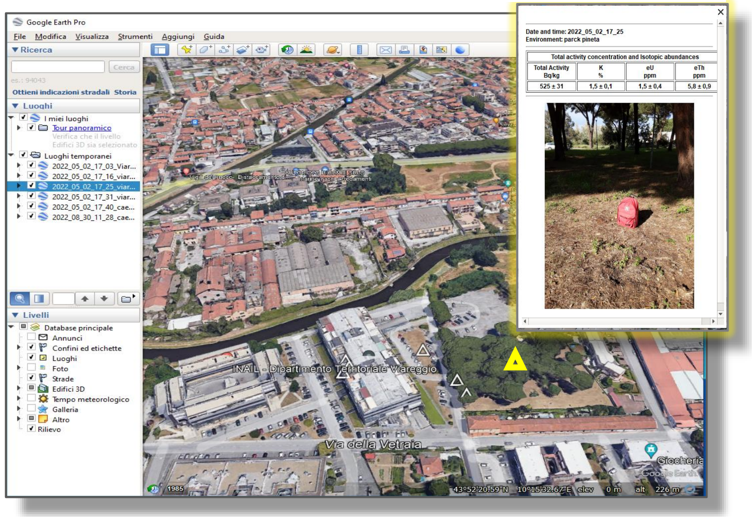
$$A = N \cdot S^{-1}$$

Calibration site characterized by known abundancies (A) of U, Th and U.

Hands-on
(the funny part ☺)

GammaEDU Backpack

Google
Earth
Software



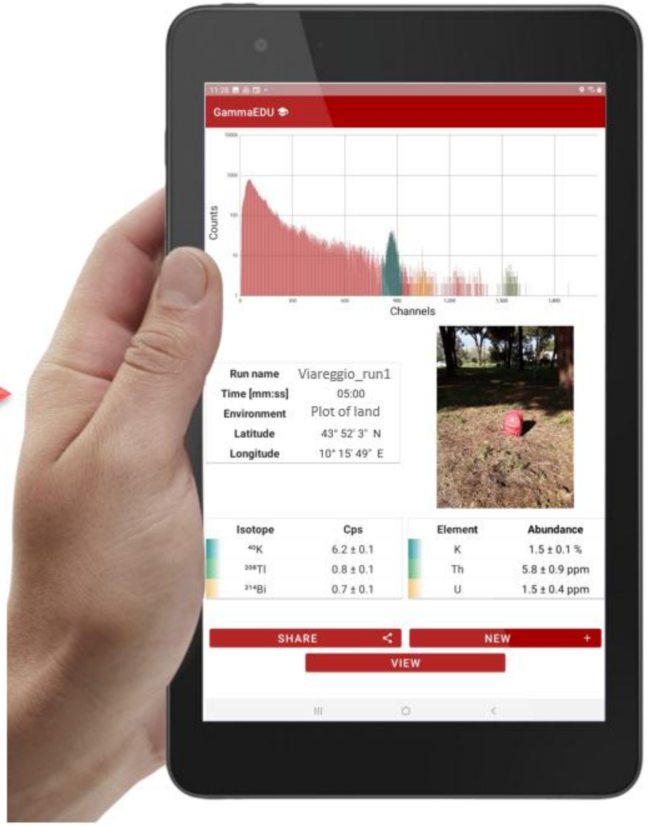
- Press the power button
- Verify that the status light is green
- Place the backpack at the point of interest

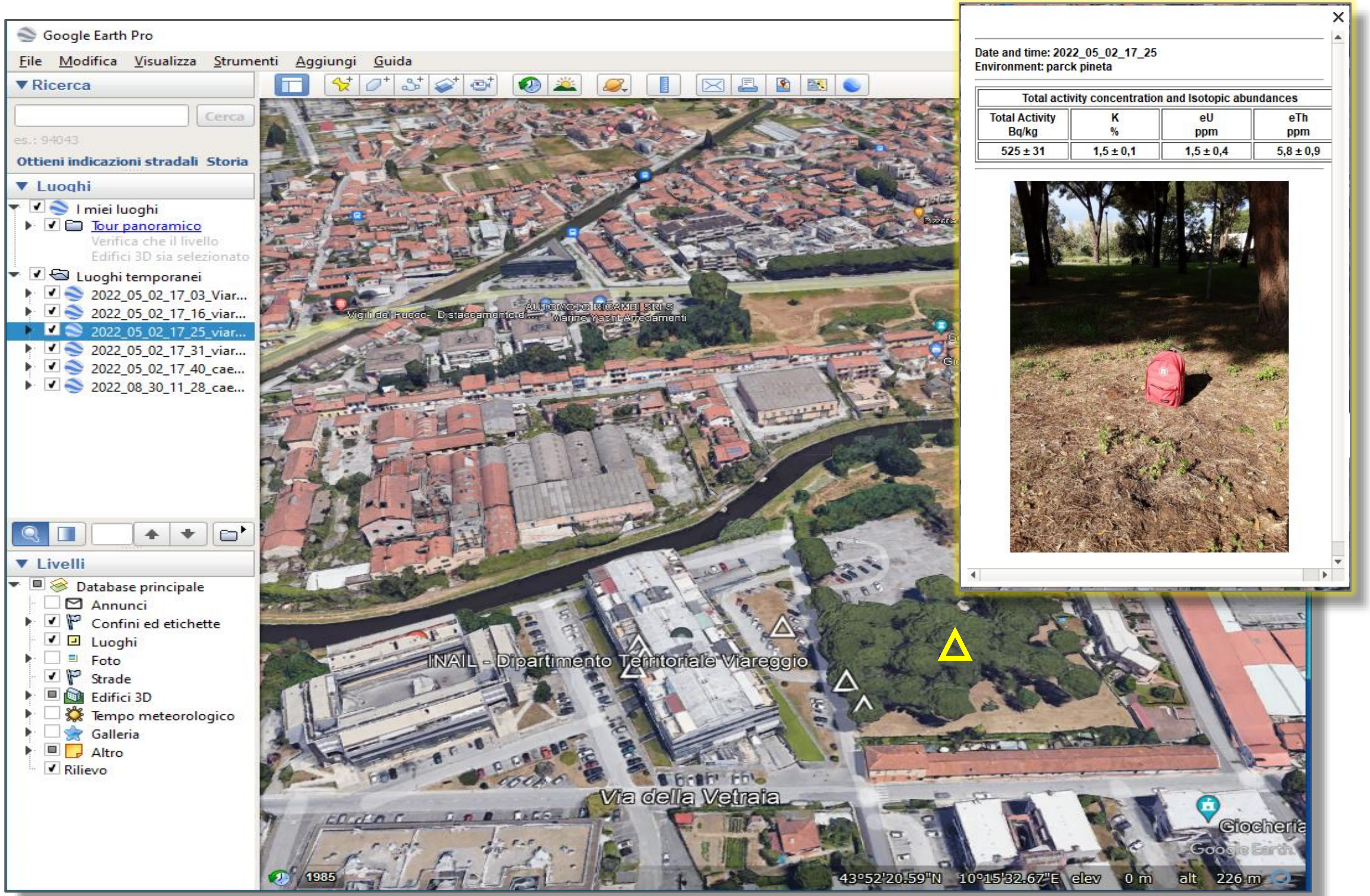
GammaEDU use (2)

- Activate the tablet and connect it via Bluetooth to the instrument
- Connect the tablet to a WIFI network
- Launch GammaEDU App
- Select «New Acquisition»

GammaEDU use (3)

GammaEDU use (4)





Total activity concentration and Isotopic abundances			
Total Activity Bq/kg	K %	eU ppm	eTh ppm
525 ± 31	1,5 ± 0,1	1,5 ± 0,4	5,8 ± 0,9

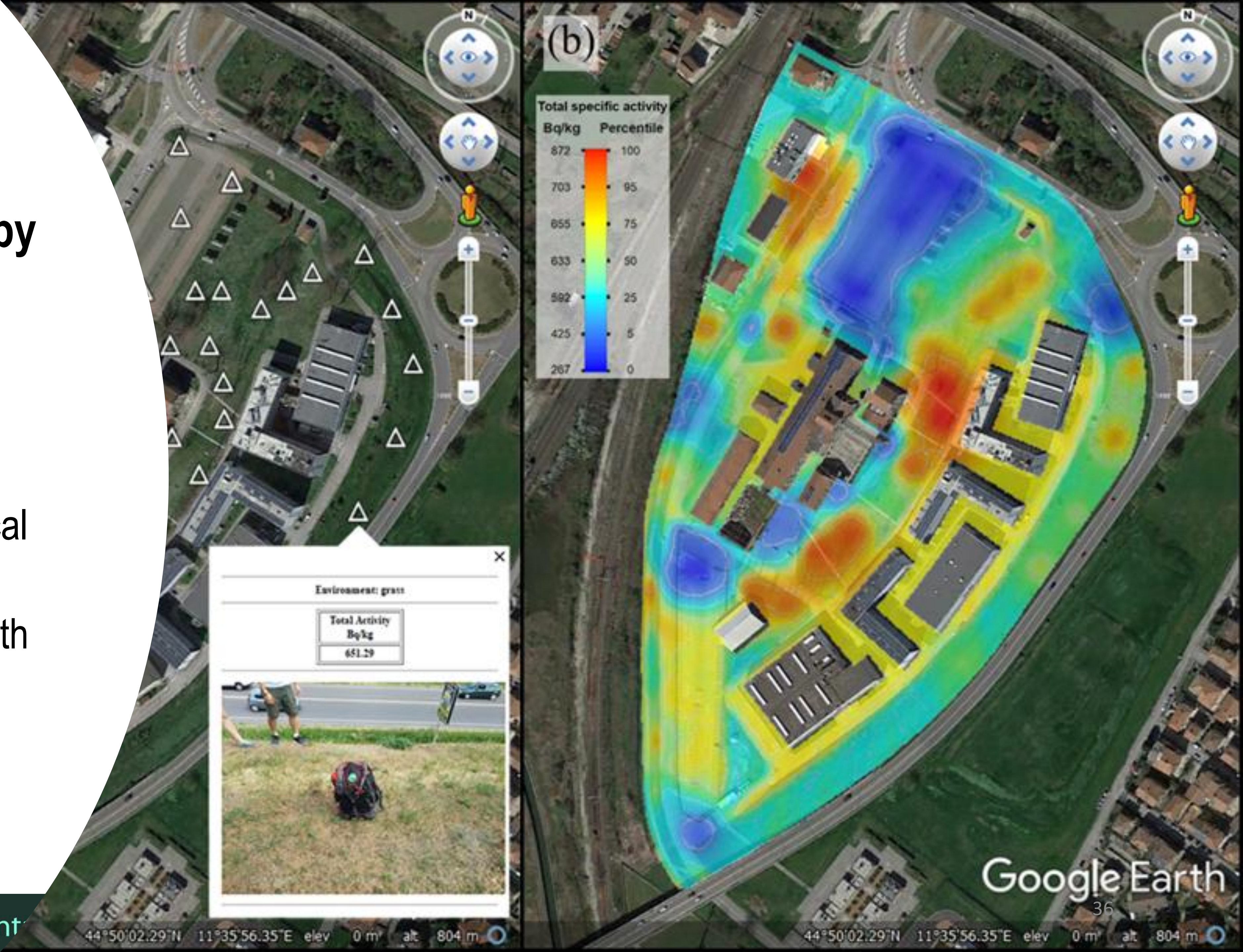
CAEN, Viareggio

Typical abundancies

^{40}K	0.02 g/g [2%]
^{238}U	3 µg/g [ppm]
^{232}Th	10 µg/g [ppm]

Gamma spectroscopy in situ

- distribution of natural or artificial radioisotopes
- study possible radiological contamination
- studies in the field of earth sciences



Is this building radioactive?

•The main contributor on the overall natural indoor radioactivity is **222/220-Rn → U-238, Th-232**

•Emissions can be measured through **photopeaks**:

- •K-40 → **1460 keV**
- •Tl-208 (from Th-232) → **2614 keV**
- •Bi-214 (from U-238) → 609 keV, **1764 keV**

•**Compare indoor radiation** to typical environmental background or soil values.

Student Tasks:

- 📊 Measure background vs wall/floor material spectra (5 minutes acquisition)
- 🔍 Identify peaks → Assign isotopes.
- 📐 Estimate activity by comparing counts to a reference sample (e.g., earth's crust)

	Isotopic Abundances		
	^{238}eU [ppm]	^{232}Th [ppm]	^{40}K [%]
Reference Values Range	[2 ; 2.5]]	[8 ; 12]]	[2 ; 2.5]]
Tuff Dwelling (4° floor)	10 ± 1	31 ± 1	6.9 ± 0.2
Modern Building (1° floor)	2.8 ± 0.6	8.8 ± 1.1	1.6 ± 0.1
Country House (0° floor)	6.8 ± 0.9	17.6 ± 1.6	3.4 ± 0.2

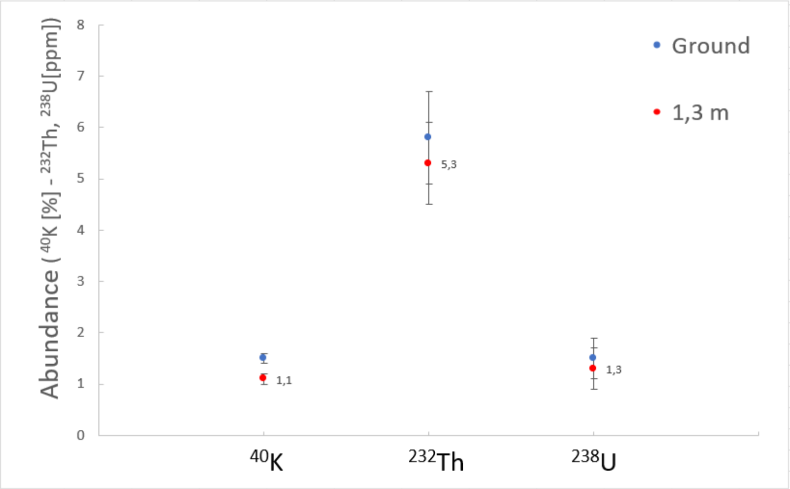
How does height matter?

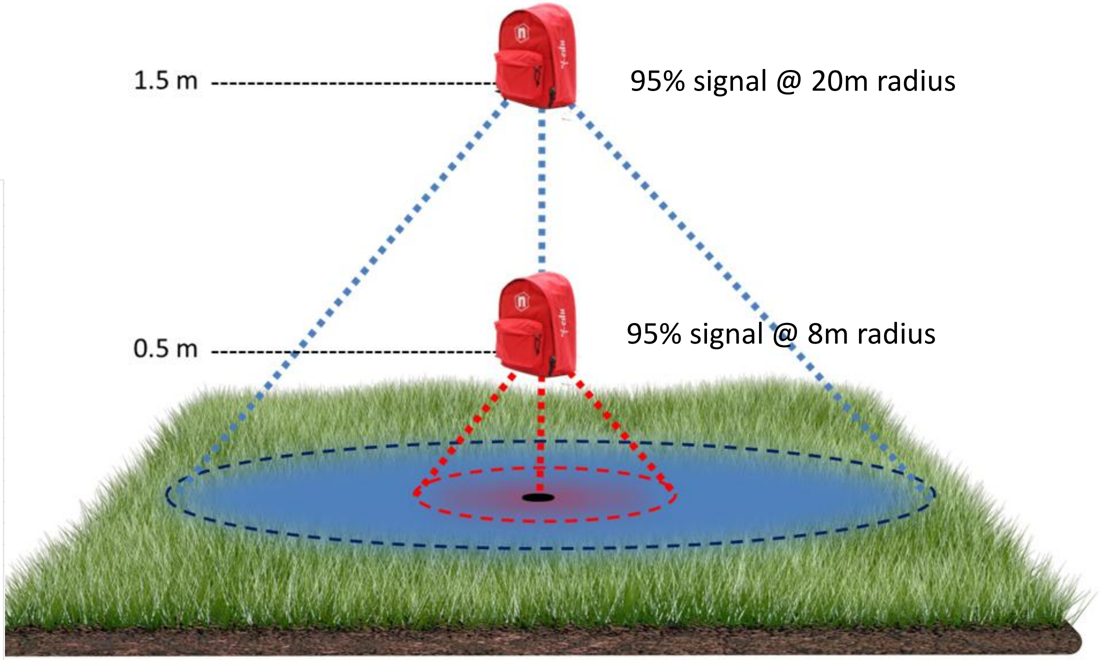
•Soil emissions are **attenuated by distance and air** → lower intensity as you move away.

•**Attenuation in air** (for extended sources like soil) → $I(d) = I(0) \cdot e^{-\mu d}$
- $I(0)$ is the count rate at the surface
- μ is the **linear attenuation coefficient** (gamma energy and medium)

•The **height of the detector** affects the **lateral horizon** – i.e., **how far around** the detector the signal originates. In practice, you observe an **initial steep drop**, then a flattening due to wide angular coverage of the detector and scattering.

Student Tasks:
- 📊 Acquire spectra at several heights: 0 cm, 0.5 m, 1.5 m
- 📈 Plot count rate vs distance.
- 🧮 Fit the data





Thanks for your attention!

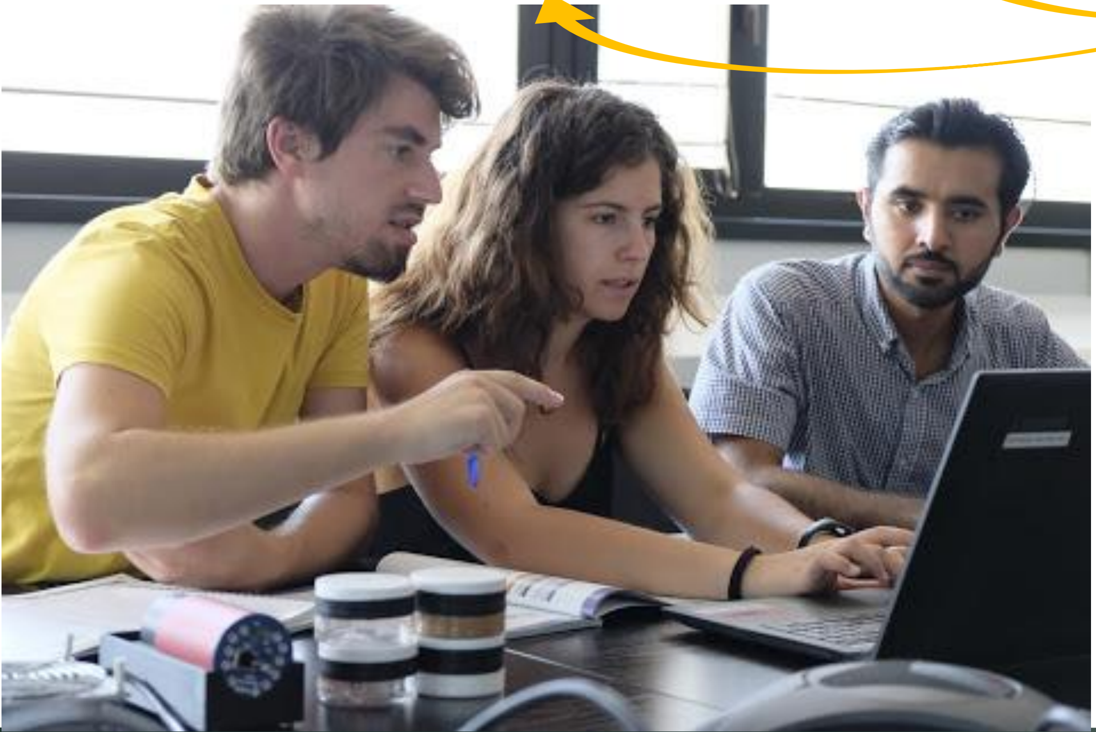
Yuri Venturini on behalf of CAEN SpA

Educational kit suggested for the environmental radioactivity experiments

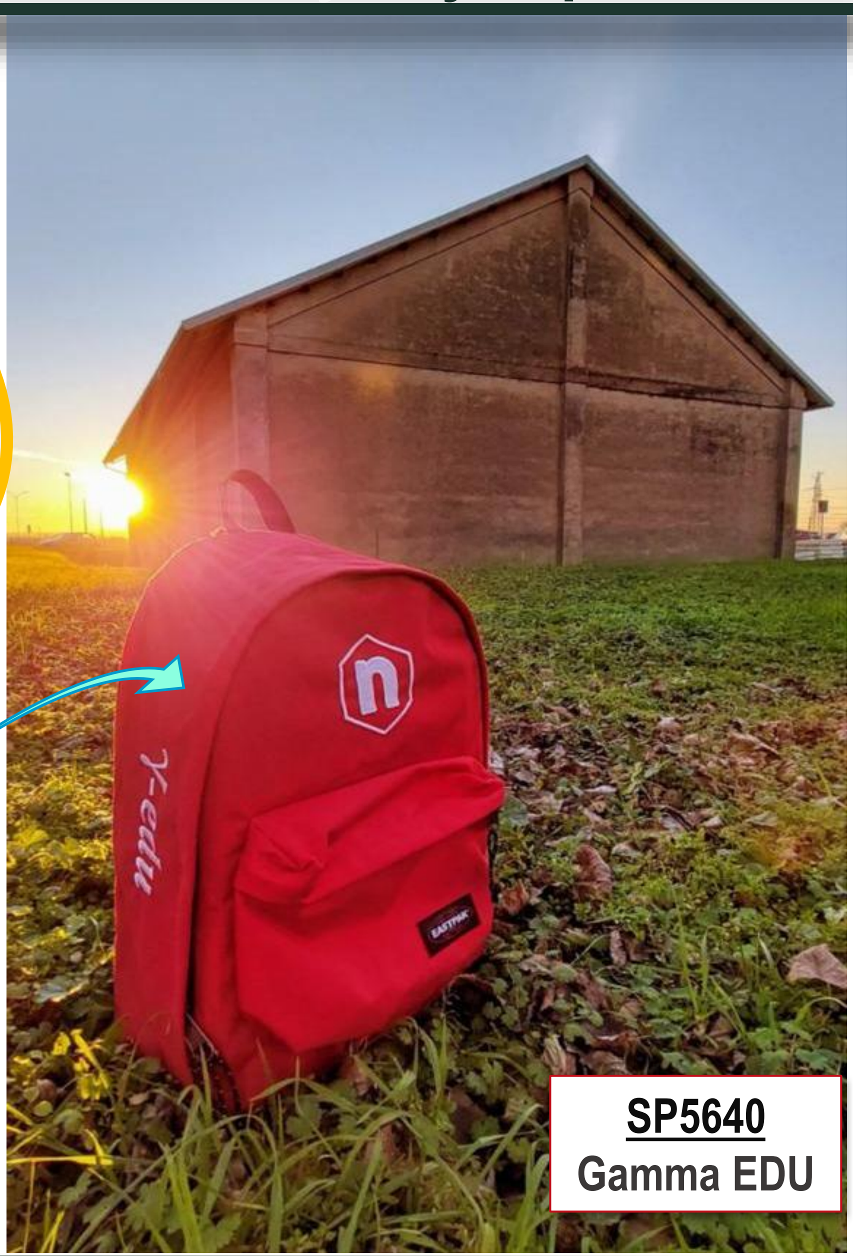
SP5630EN
Environmental kit

SP5630ENP
Environmental kit Plus

Two solutions for environmental radioactivity indoor!



Environmental radioactivity Outdoor!



SP5640
Gamma EDU

...About GammaEDU

SP5640 – GammaEDU

RadioLAB

IRSOIL&WATER 2023

Spring School

Calabria, Italy
April 2023

I.C. Don Lorenzo Milani

Viareggio, Italy
May 2023

High School Students

Tuscany, Italy
May 2022

RADIOLAB

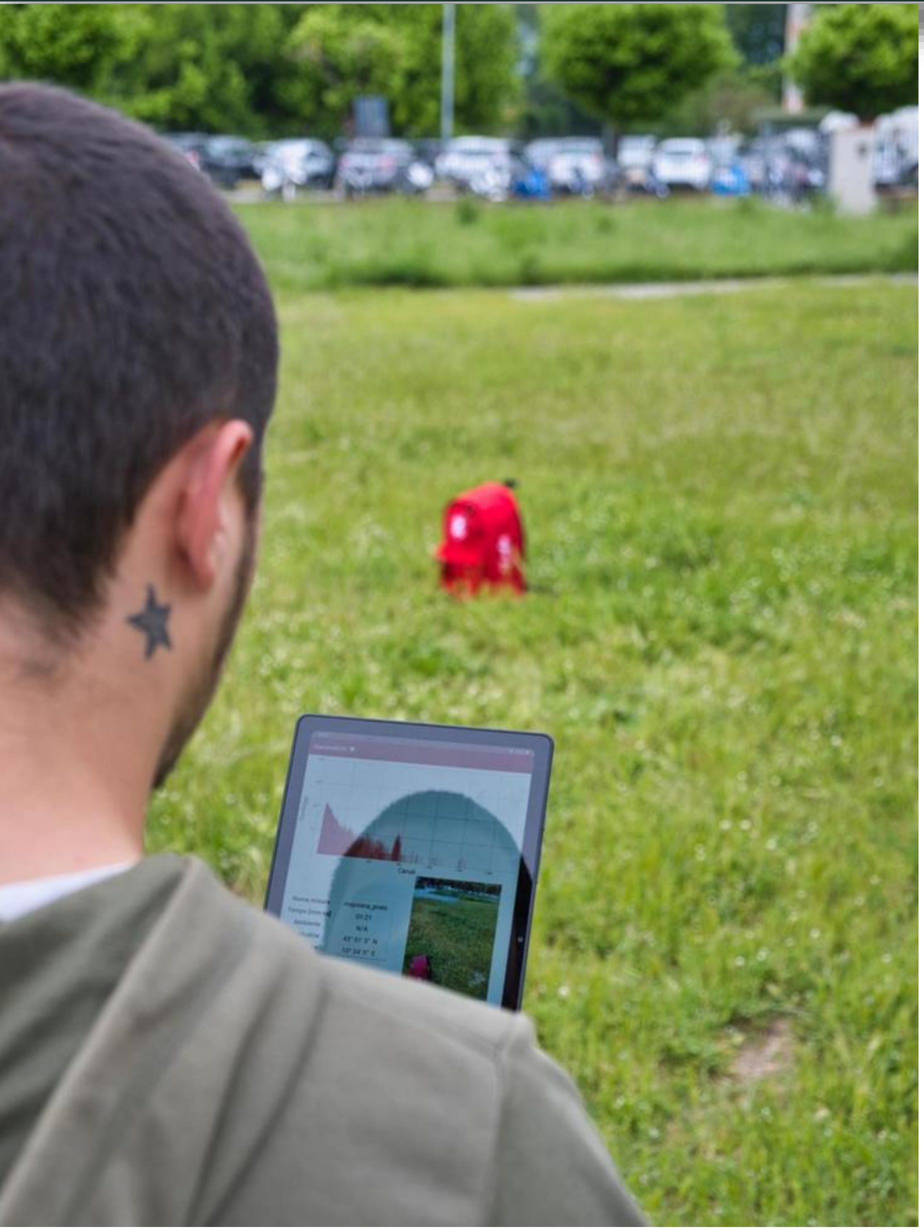
INFN Istituto Nazionale di Fisica Nucleare

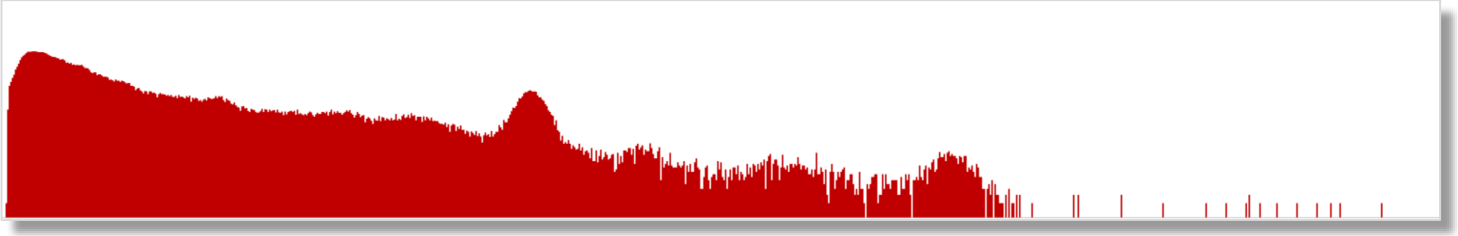
Portable detection backpack for environmental radioactivity!

RadioLAB Project

Sicily, Italy
April 2023

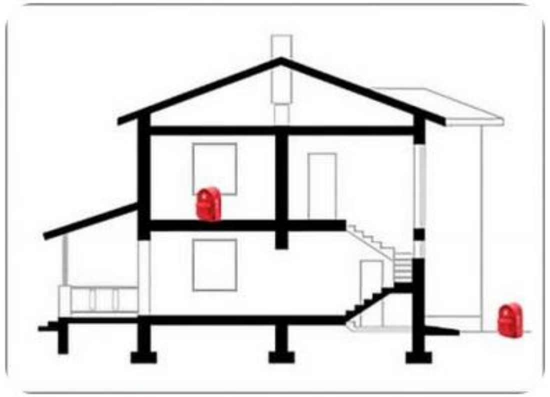
γ Environmental Radioactivity (outdoor)



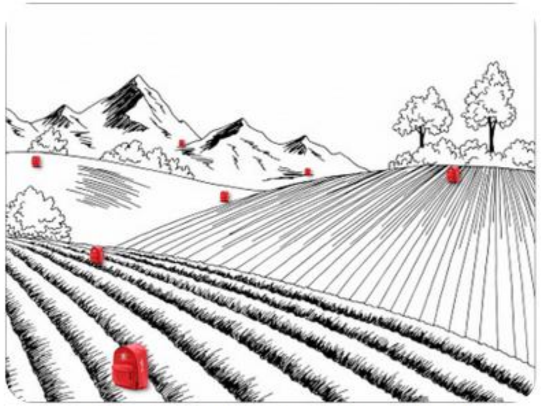


			Equipment									
Section	**Subsection**	**Experiment**	SP5600C	SP5600D	SP5600E	SP5600AN	SP5600EMU	SP5700	SP5701	SP5620CH	SP5630EN	**SP5640**
Nuclear Physics and Radioactivity	**γ Environmental Radioactivity (outdoor)**	*Environmental monitoring in land field*										✸
		γ Environmental Detection as a function of the soil distance										✸
		Radioactivity maps production									✸	✸
		Mapping of potential radon-prone areas									✸	✸
		Radiological evaluation of the building materials									✸	✸
		Geochemical and mineral exploration									✸	✸

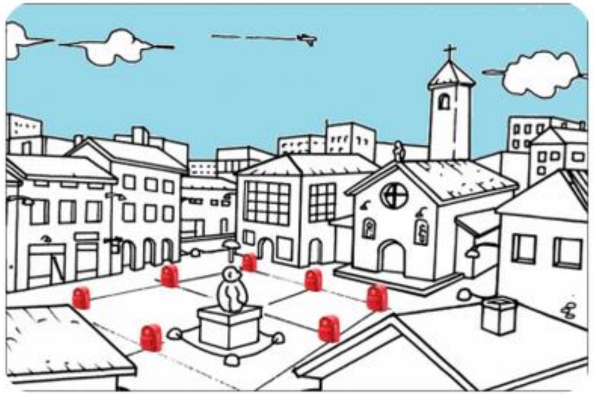
Suggested Experiments



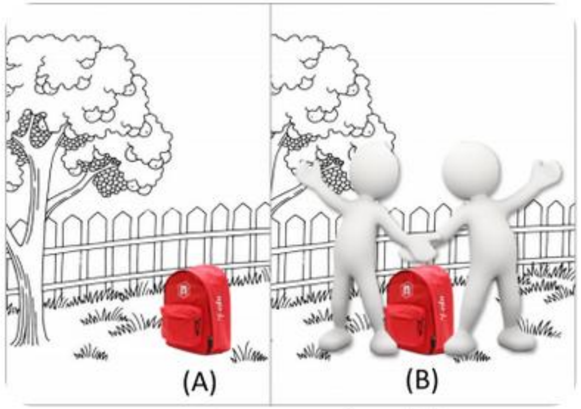
Radiological evaluation of the building materials



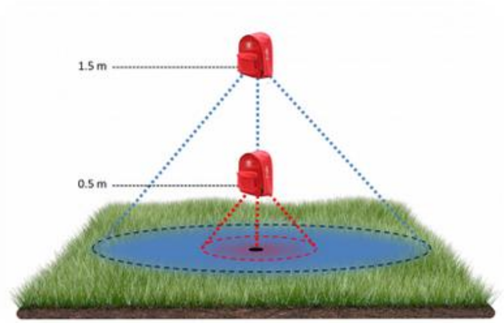
Geochemical and mineral exploration



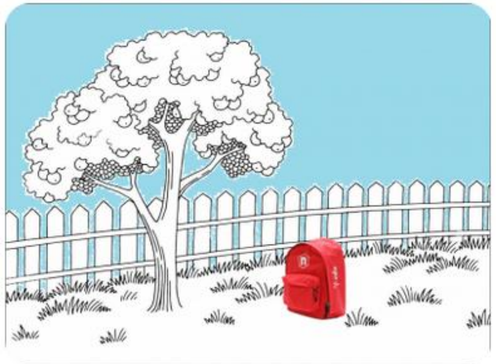
Radioactivity maps production



Human body Radioactivity

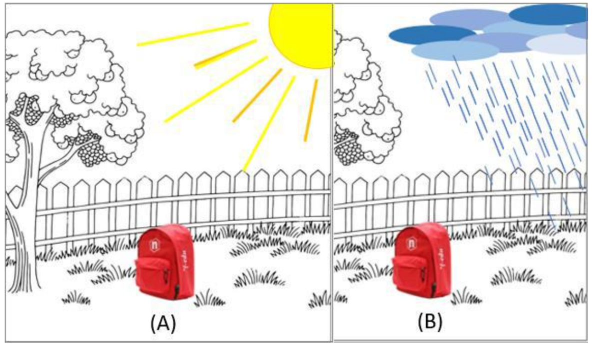


γ Environmental detection as a function of the soil distance

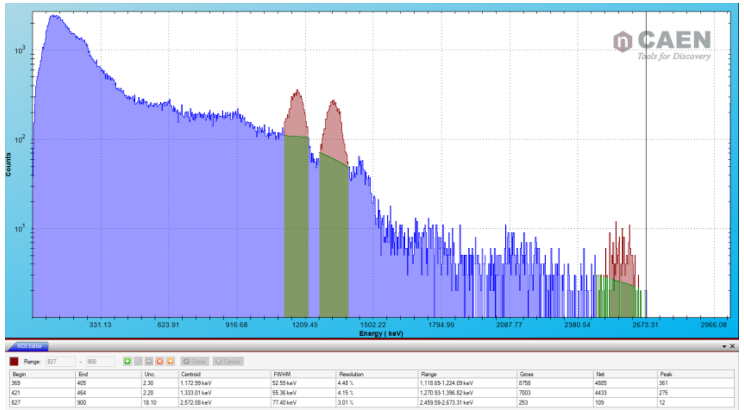


Environmental monitoring in field

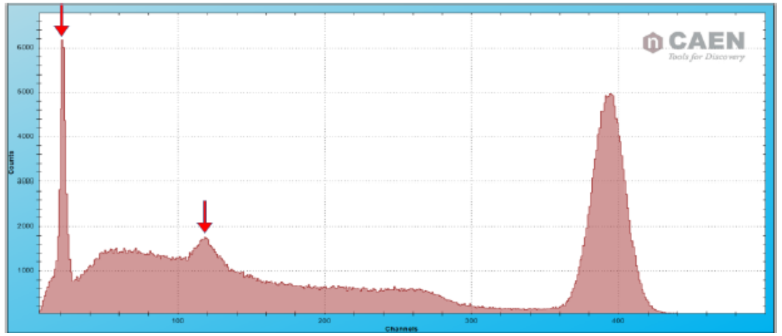
Ground coverage Effect on the Environmental Monitoring



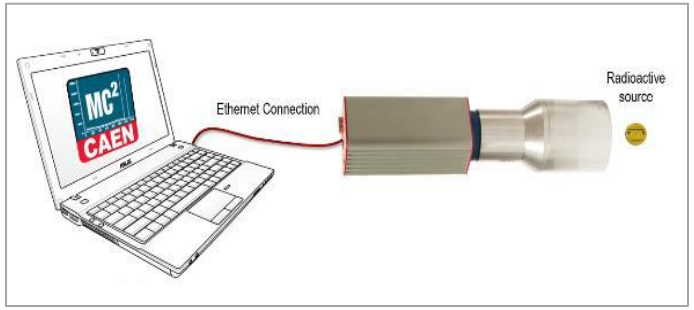
Soil water content evaluation with gamma ray spectroscopy



Activity of the ^{60}Co



Study of the 137Cs spectrum: the backscatter peak and X rays



Measurement of Photomultiplier Plateau Curves

Detecting γ-radiation

Poisson and Gaussian Distribution

Energy Resolution

System Calibration: Linearity and Resolution

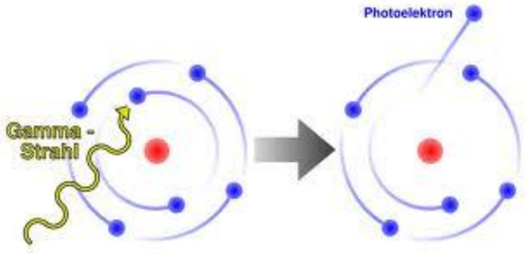
γ-Radiation Absorption

Photonuclear cross-section/Compton Scattering cross-section

Gamma interaction with matter

Photoelectric effect

[γ + atom→ion + e^-]

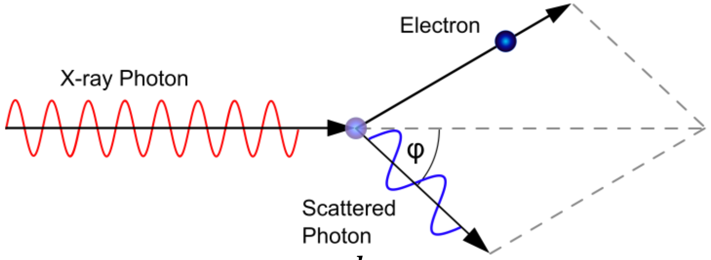


$$E_e = h\nu - E_b$$

- 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

Compton effect

[γ + e^- → γ' + $e^{-\prime}$]

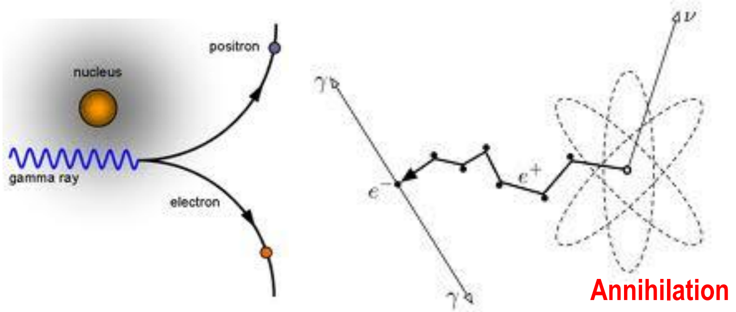


$$E'_\nu = \frac{h\nu}{1 + \frac{h\nu}{m_0 c^2}(1 - cos\theta)}$$

- Photon interacts atomic electrons of the absorber material
- The interacted photon is scattered with a certain angle (q) 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-Nishima Formula
- Typical interaction of radioisotope energy, hundreds of keV region

Pair production

[γ + nucleus → e^+ + e^- + nucleus]



Annihilation

- 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

SPARES

RockyRAD Educational Kit

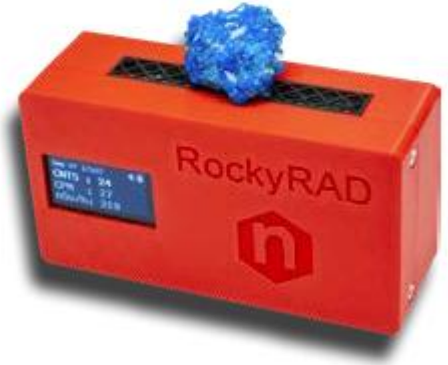
Nuclear Physics
- Statistics
- Environmetal Radioactivity

NEW

SP5660 – RockyRAD

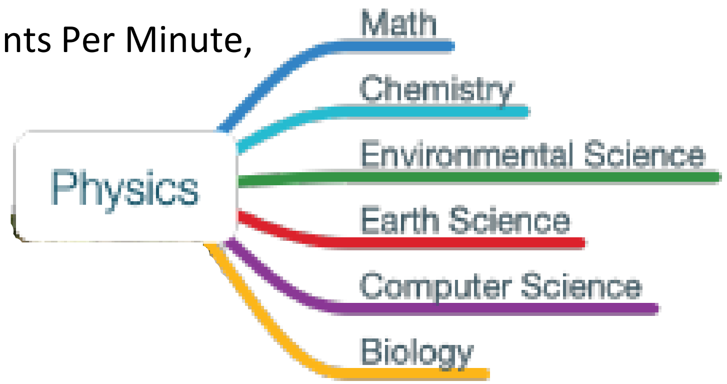
From geology to daily life, **RockyRAD** bridges the gap: discover the fascinating world of rock radioactivity and then expand your horizon to detect the unseen radiation in our everyday surroundings.

Portable Geiger Counter for nuclear radioactivity radiation!



Each **RockyRAD kit** is enhanced with a set of rock samples from different origins, allowing students to immediately begin their detection experiments.

- *Detector*: Geiger-Müller Tube
- *Display Information*: Total Counts, Counts Per Minute, Equivalent Dose Rate
- *Wi-Fi* for data download
- *Bluetooth* connection
- *Rechargeable Battery* (USB-C)



Android App under development!

Educational kit suggested for the environmental radioactivity experiments

SP5630EN
Environmental kit

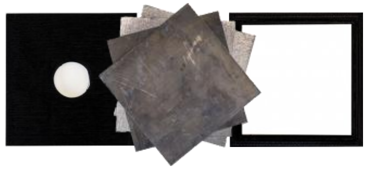
S2570B i-Spector Digital
18x18mm^2 - ASSEMBLY
(CsI 18x18x30mm^3)

Samples

SP5630ENP
Environmental kit Plus

S2570D i-Spector Digital
18x18mm^2 - CsI ASSEMBLY

BGO scintillating crystal



Shielding Kit

Samples

SP5640
Gamma EDU

S2580 GAMMASTREAM
Digital MCA Tube Base

NaI(Tl) [0.3l] scintillation detectors

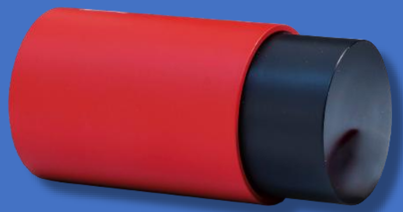
Tablet 10"

SP5630EN – Environmental kit Description

Environmental gamma radiation measurements with SiPM based instrumentation!

Web-based GUI for unit control and data analysis

SP5630EN – Environmental kit



S2570 - i-Spector Digital

- The system is based on a SiPM area 18 × 18 mm^2
  All SIPMs of the area are connected in parallel to increase the active area of the matrix.
- It integrates a shaper, a peak stretcher and a peak ADC to implement a simple MCA (4K).
- Scintillator Crystal: CsI 18 x 18 x 30 mm^3
- Connectivity: Ethernet
- Software: Web GUI

Samples

Empty Beaker & Test Sample

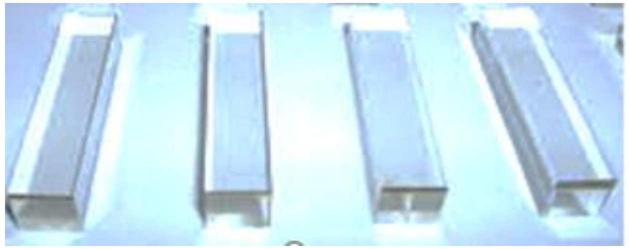
Fertilizer and Rock Samples

Canisters of Activated Carbon

Calibration Crystal ($Lu_{1.8}Y_{.2}SiO_5:Ce$)

LYSO (Lu1.8Y.2SiO5:Ce) (Cerium-doped Lutetium Yttrium Orthosilicate) Scintillating Crystal

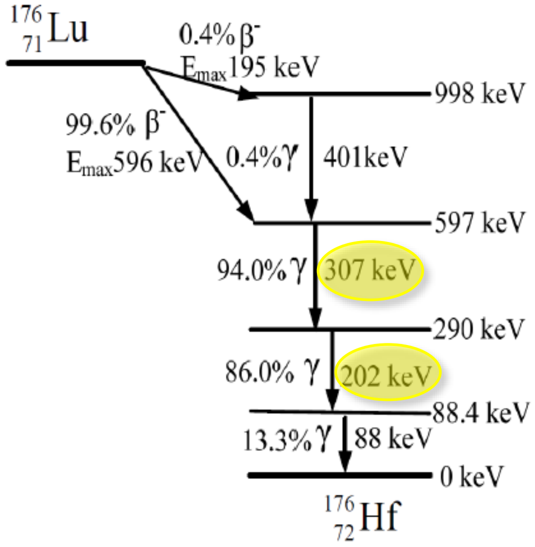
Scintillator based on Lutetium (Lu) like **LSO** and **LYSO** (**Lu1.8Y.2SiO5:Ce**) are usually used in PET applications thanks to their high stopping power (high Z), high light yield and very short decay time (very fast signals). It is a non-hygroscopic scintillator.

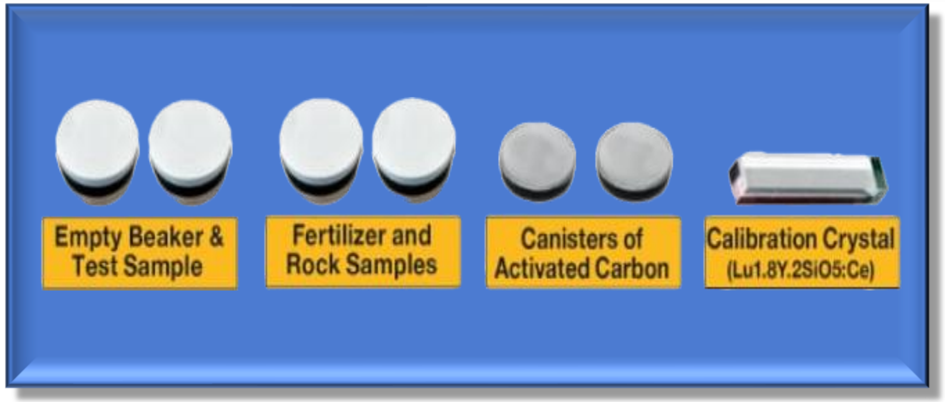


Properties	Value
Cleavage Planes	None
Decay Constant (ns)	40
Density (g cm^{-3})	7.1
Emission Spectral Range (nm)	380-480
Melting Point (K)	2323
Peak Scintillation Wavelength (nm)	420
Photons/MeV	32000
Radiation Length (cm)	1.15
Refractive Index at Peak Emission	1.81
Solubility (g/100g H_2O @ 300K)	Insoluble
Stability	Good
Structure	Cubic

2,6% of the natural Lu is ^{176}Lu, a radioisotope with a long half life decaying via two different beta decays followed by gamma emissions.

$$T_{1/2} \sim 3{,}6 \times 10^{10}\ y$$





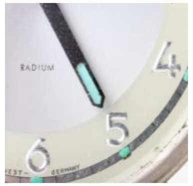
Potassium Phosphate fertilizer

Rocks

Test Sample

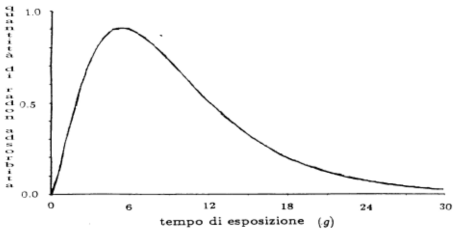
One of the radioactive objects of common use, in past especially.





Canisters of Activated Carbon for Radon Passive Measurements

- Diameter: 10 cm
- Height: 3 cm
- Content: 70 g of activated carbon



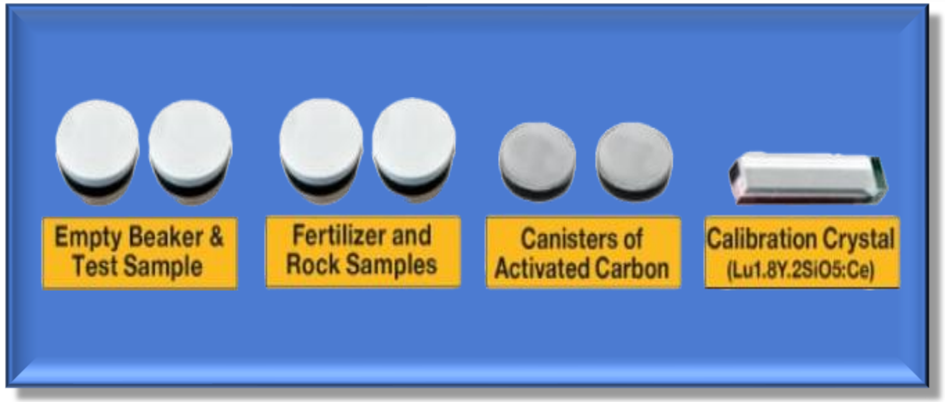
The activated carbons are enclosed in metal containers called "canisters".
Covered by a thin double-mesh metal mesh (diffusive barrier).
The diffusion barrier serves to eliminate the air flows inside the basket, which can favor the re-emission of radon.

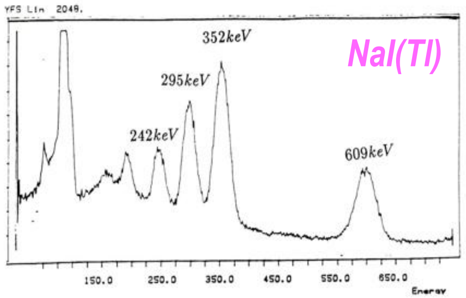
The method consists in carrying out gamma spectrometry measurements on the baskets after the radon has been adsorbed by them!

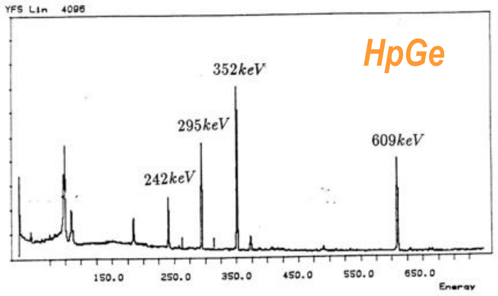
After 6-7 days, the loss due to decay prevails over the accumulation by adsorption.

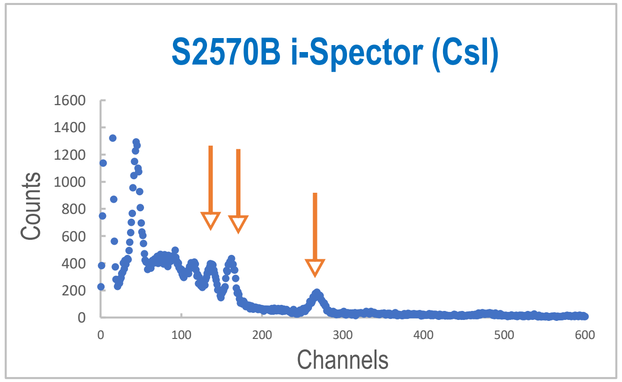
Features:

- useful for short-term measurements: 2 - 7 days
- strong dependence of the response on humidity







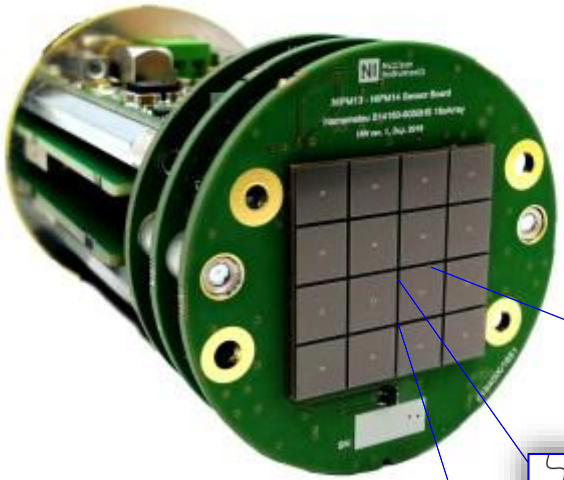


Gamma Energy lines:

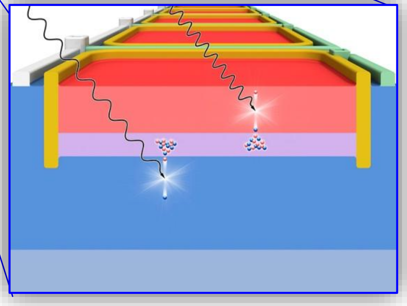
- 295 keV and 352 keV from ^{214}Pb
- 609 keV from ^{214}Bi

i–Spector Digital [S2570B-S2570D]

Almost equal except for their mechanics and for the components distribution on the PCBs!



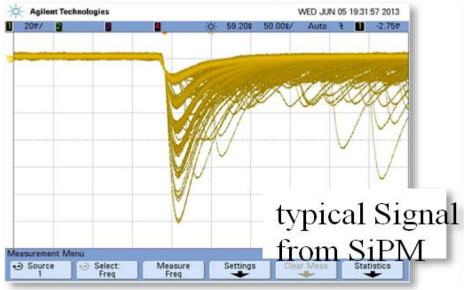
- The systems are based on a SiPM area 18 ×18 mm^2
  Hamamatsu S14160-60520HS
  All SIPMs of the area are connected in parallel to increase the active area of the matrix.

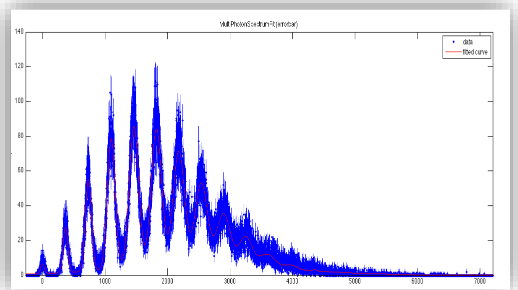


Silicon Photomultiplier (*SiPM*) are high density (up to 10^4/mm^2) matrix of diodes with a common output, working in Geiger-Müller regime.
Each cell is a pixel with a binary signal.
It can detect a single photon!

- *High Gain*
- *Low Voltage*
- *High photon number resolving power*
- *Wide dynamic range*
- *Good timing capability*
- *Low cost*
- *Withstanding to magnetic field*

The high uniformity of pixel structure guarantees no avalanche fluctuations

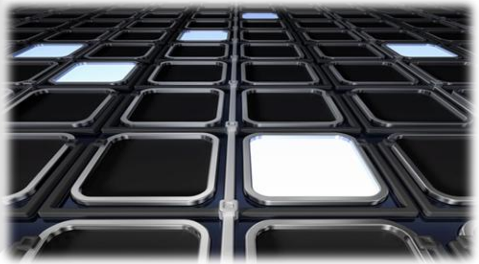




Linear response if the average number of photoelectrons/pixel is less than one

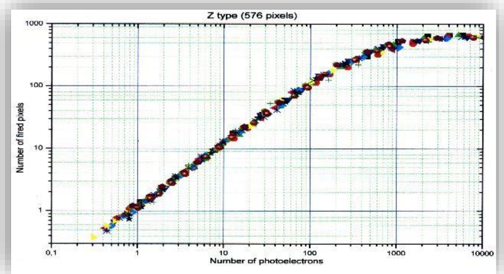
Number of pixel determines the SiPM **dynamic range**

Binary information



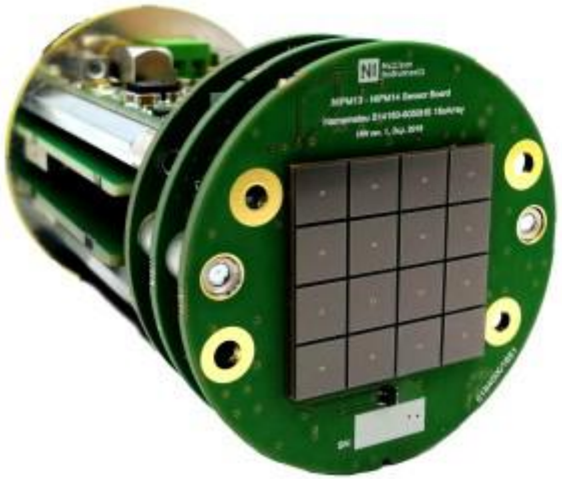
$A = \Sigma A_i$

Analog information



i–Spector Digital [S2570B-S2570D]

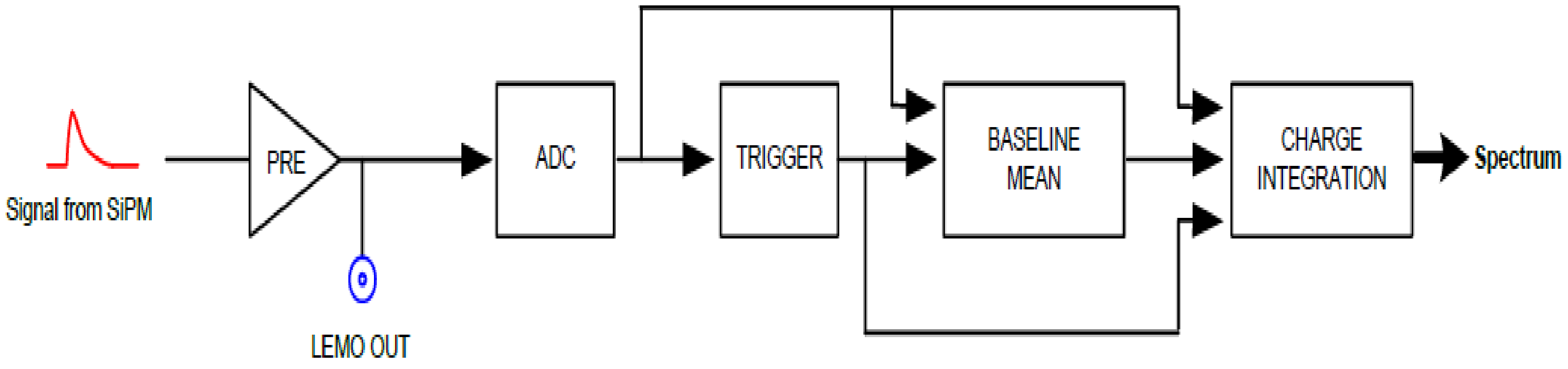
Almost equal except for their mechanics and for the components distribution on the PCBs!



- The systems are based on a SiPM area 18 ×18 mm^2 **Hamamatsu S14160-60520HS** All SIPMs of the area are connected in parallel to increase the active area of the matrix.
- They integrate a shaper, a peak stretcher and a peak ADC to implement a simple MCA (4K).
- Scintillator Crystal: CsI 18 x 18 x 30 mm^3
- Energy Range: 30 keV to 3 MeV
- Energy Resolution (FWHM): <6 % @ 662 keV
- Connectivity: Ethernet
- Software: Web GUI

TECHNICAL SPECIFICATIONS

Supply Voltage	8-13V (12 V typ.)
Power consumption	3W max.
Preamplifier bandwidth	>1GHz
Preamplifier gain	x 5
Shaping time	180 ns
Output signal	- 4 … +4 V , 170 mA
HV Power supply	20-80 V (10mA)
HV accuracy	1 mV
Thermal feedback accuracy	0.01°C - 1mV
MCA nr. of channels	4096



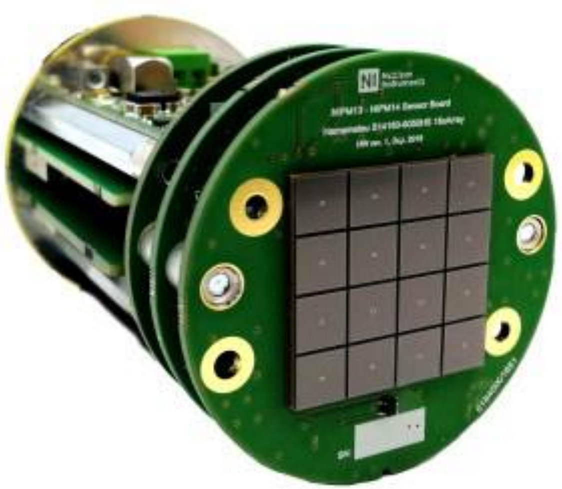
i-Spector Digital block diagram

i–Spector Digital [S2570B-S2570D]

S2570B

S2570D

Almost equal except for their mechanics and for the components distribution on the PCBs!



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Preamplifier bandwidth	>1GHz
Preamplifier gain	x 5
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Output signal	- 4 … +4 V , 170 mA
HV Power supply	20-80 V (10mA)
HV accuracy	1 mV
Thermal feedback accuracy	0.01°C - 1mV
MCA nr. of channels	4096

Web-based GUI for unit control and data analysis

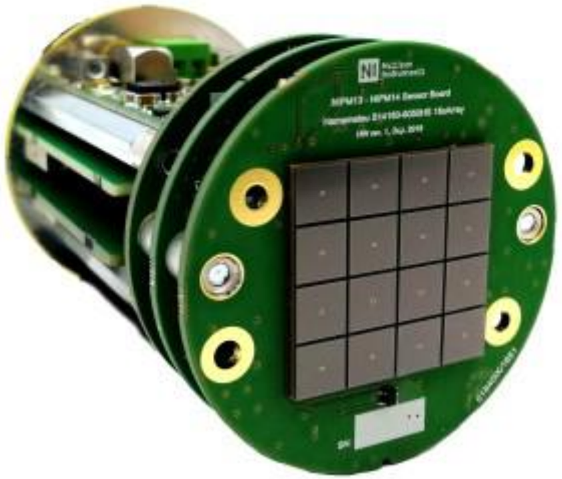
i-Spector Digital can be easily controlled through its dedicated web graphical user interface, with no needs to install a dedicated software. The user can configure the module and visualize the acquired spectrum.
Thanks to the internal circular memory buffer, the last 1-hour recording can then be downloaded by the web interface.

i–Spector Digital [S2570B-S2570D]

S2570B

S2570D

Almost equal except for their mechanics and for the components distribution on the PCBs!



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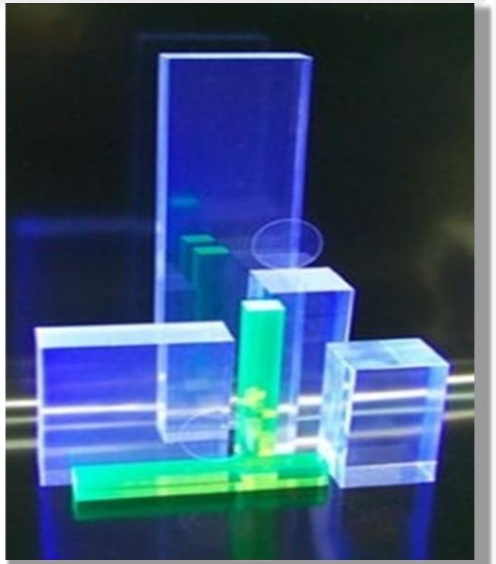
- Software: Web GUI

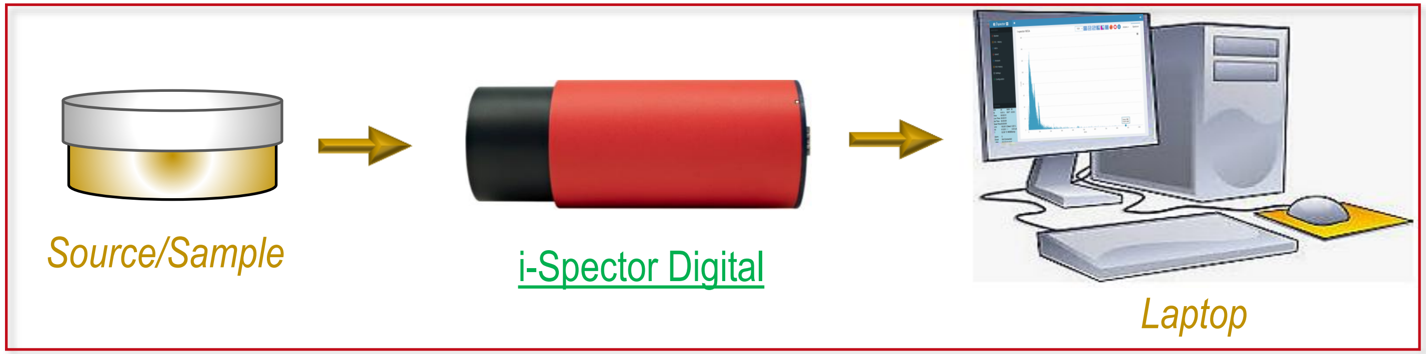
CsI(Tl) information:
This scintillator offers a high light yield and emits at a wavelength very suitable for silicon photomultipliers (SiPMs). Typical applications include arrays of this material used in security imaging systems, such as baggage scanners.

BGO information:
A relatively hard, high density, non-hydroscopic crystal with good gamma ray absorption. Often used for PET imaging and high energy physics applications as Compton shields.



Properties	CsI	BGO
Cleavage Planes	None	None
Decay Constant (ns)	1000	300
Density (g cm^{-3})	4.51	7.13
Emission Spectral Range (nm)	350-725	350-650
Gamma and X-ray absorption coefficients (cm^{-1})	0.48 at 660keV 10.00 at 100KeV	-
Melting Point (K)	894	1323
Peak Scintillation Wavelength (nm)	550	480
Photons/MeV	52000	8500
Radiation Length (cm)	1.86	1.13
Refractive Index at Peak Emission	1.78	2.15
Solubility (g/100g H_2O @ 300K)	44.0	Insoluble
Stability	Slightly Hygroscopic	Good
Structure	BCC	Cubic
Thermal Conductivity (W·m^{-1}·K^{-1}) @ 300K	1.13	-
Transmission Range (nm)	240-70000	470-7500

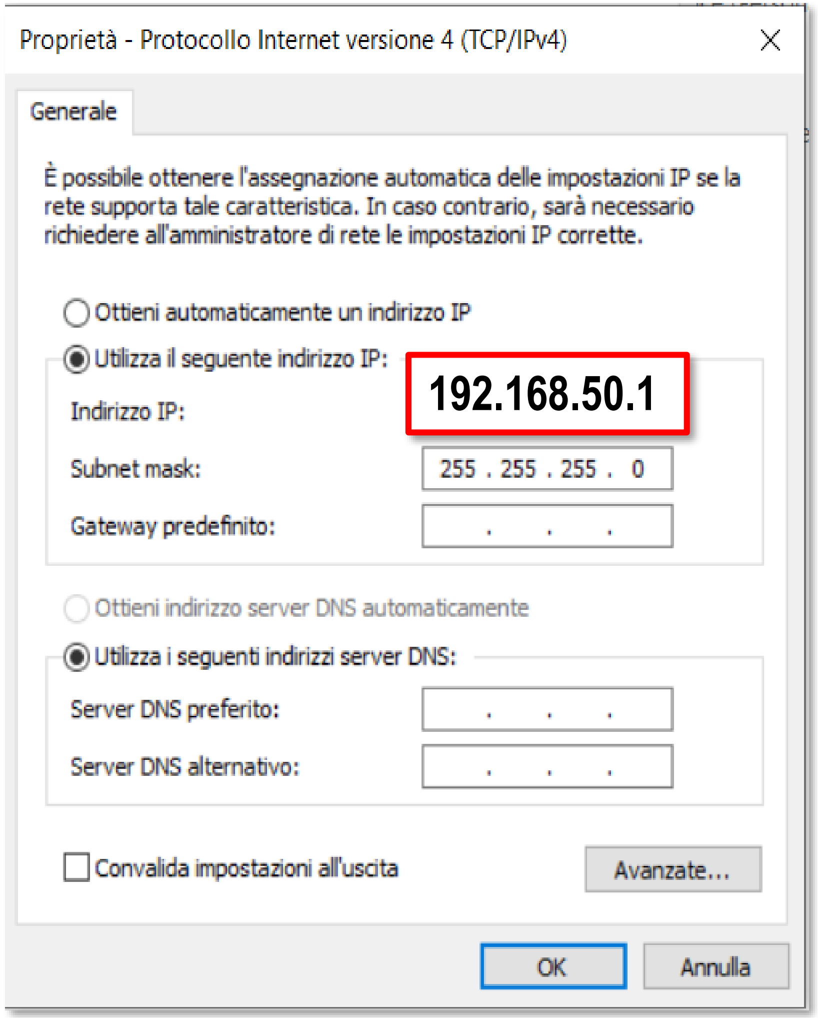
Hands-On…



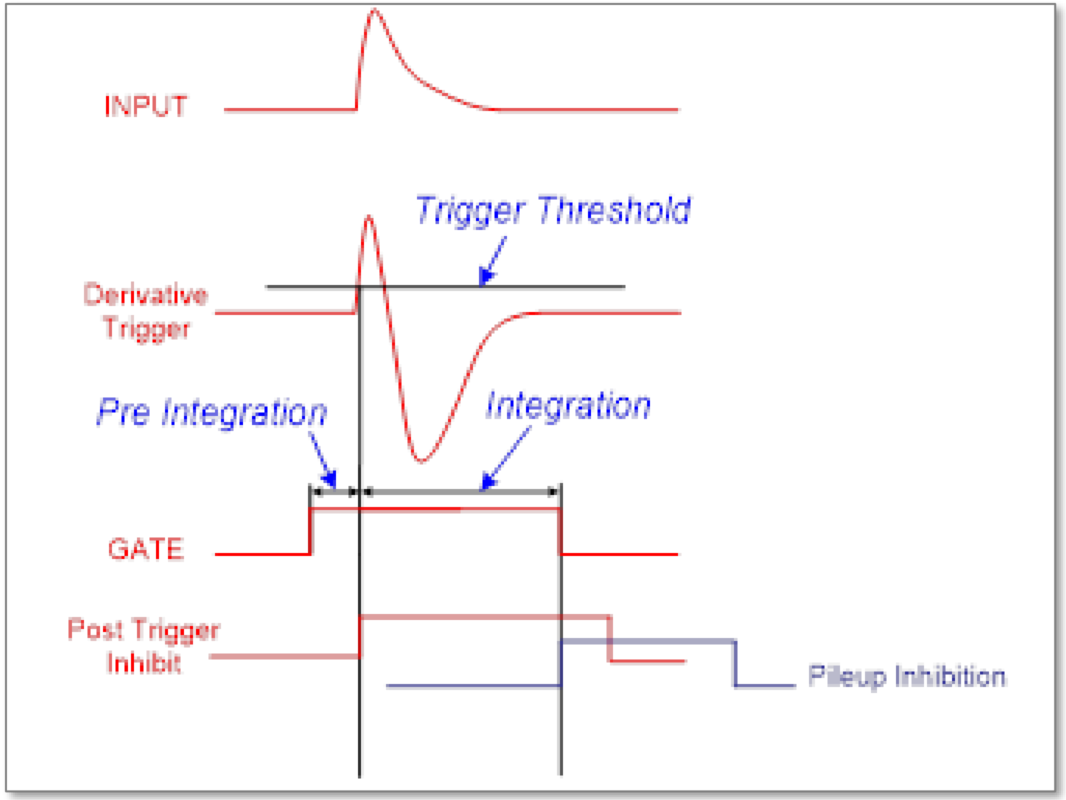
1. Unboxing and Assembling
2. Software Setup
3. Energy calibration of the system based on LYSO crystal (time base = 10’)
4. Calibration verification and tuning with Potassium Chloride sample (time run = 30’)
5. Background measurement (time run = 30’)
6. Rock sample Spectrum (time run = 30’)
7. Test sample radiation identification
8. Analysis of spectra and superposition
9. Passive Radon Measurements

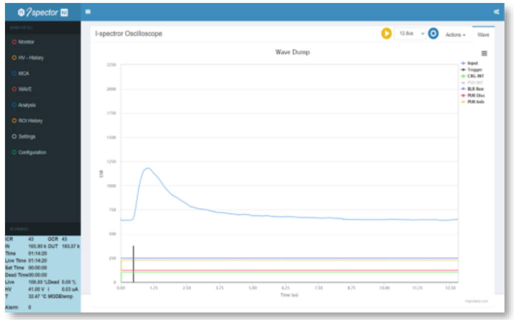
c.mattone@caen.it

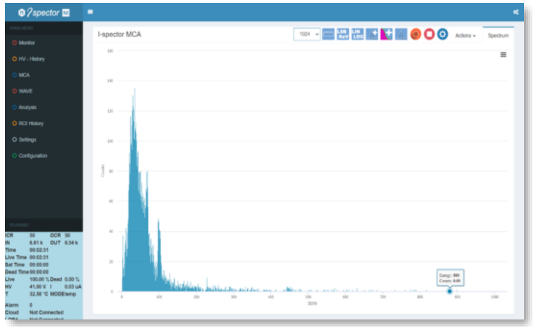
- **IP address** of the i-Spector for Ethernet connection is **192.168.50.2**
- Configure the Ethernet network of the PC from the “Network and Sharing Center”
- Open a web browser (**Microsoft Edge browser is suggested**) and enter the web address **192.168.50.2**. The homepage of the graphical web interface will open.



Software Setup - Parameters of the charge integration algorithm





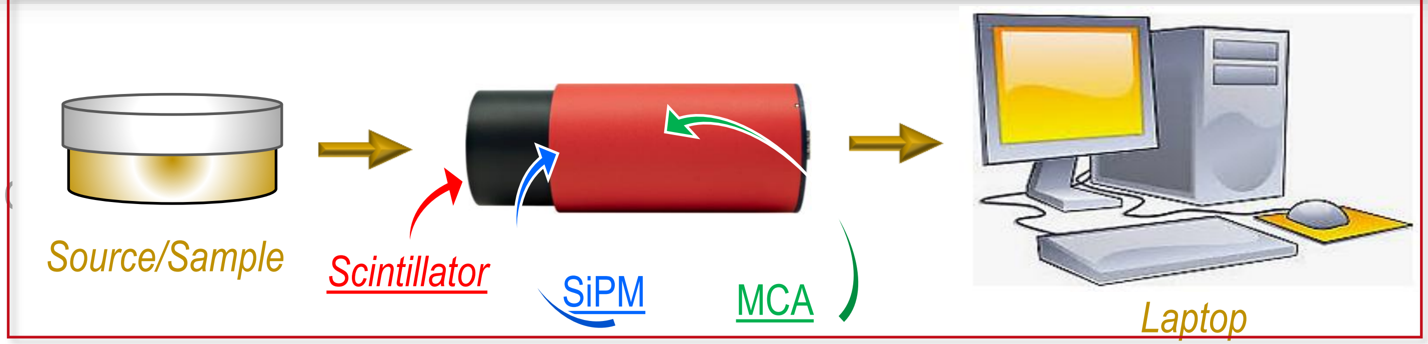


- *Trigger Threshold (LSB):* threshold for the derivative trigger
- *Post Trigger Inhibit (ns):* set the time after a trigger for which any other trigger is inhibited
- *Pre-Integration (ns):* set how much time before the trigger the charge integration is started
- *Integration (us):* set the charge integration gate
- *Gain:* set the energy digital gain to be applied to the spectrum
- *Pileup Inhibition (us):* set the time after the integration gate for which the acquisition of any other event acquisition is inhibited
- *Pileup Penality (us):* set the trigger inhibition gate to be opened after a pile up
- *Baseline Inhibition (us):* set the time after the integration gate for which the baseline is not calculated
- *Baseline Length (samples):* set the number of samples used to calculate the baseline
- *Target Mode:* set the acquisition mode as Free Running or with a targe in Time (ms) or Counts
- *Target Value:* set the target value in time or counts, accordingly to the Target Mode

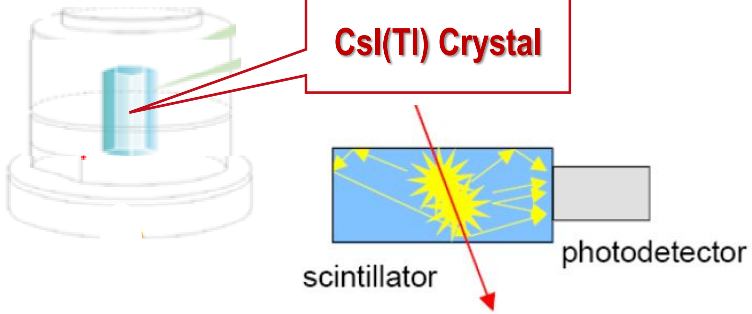
1) **How to use the i-Spector Digital**

2) Energy calibration of the system based on LYSO (

3) Background measurement (time run = 30')



Scintillator



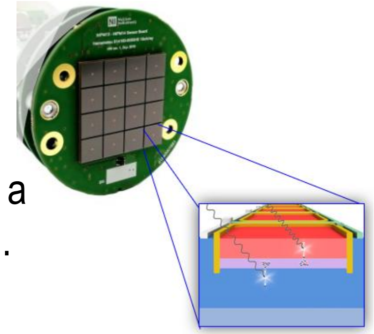
Energy deposition by an ionizing particle:

- Generation of light
- Transmission of scintillation light
- Detection

CsI(Tl) has a light output of 54 photons/keV and average decay time of about 1μs for γ-rays

Silicon Photomultiplier (SiPM)

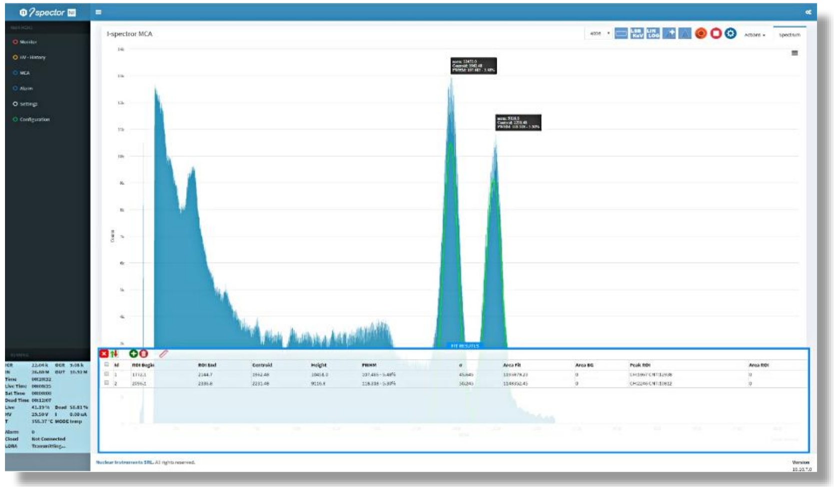
Silicon Photomultiplier (SiPM) is detector made of a matrix of silicon cells (diodes). Each dinode is a pixel with a binary signal. It can detect a single photon!



Photosensors detect and transform the light produced by the scintillator into an electrical signal. This signal is proportional to the energy released inside the crystal by the interacting particle

Electronics & Analysis Software

The output pulses are proportional to the energies of the incident radiation, the ADC is used combined to a Multichannel Analyzer (MCA) to generate energy distributions (spectra) of radioactive samples



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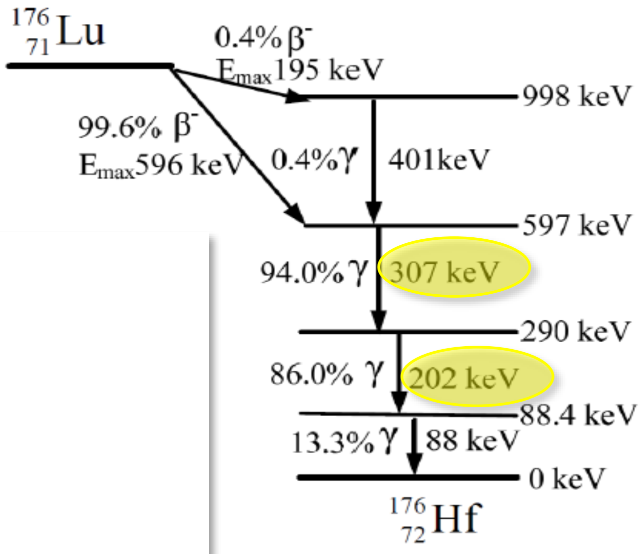
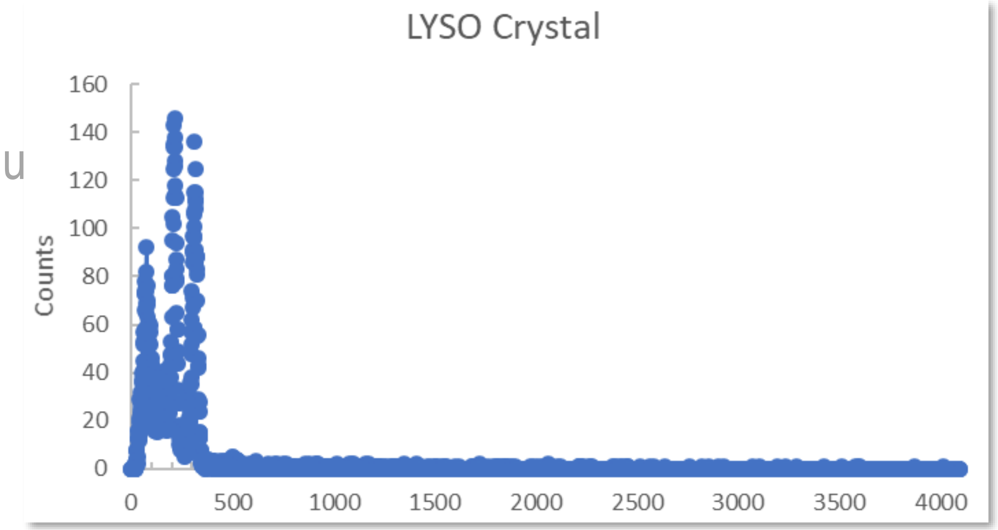
5) Rock sample Spectrum (time run = 30')

6) Test sample radiation identification

7) Analysis of spectra and superposition

8) Passive Radon Measurements





Scintillator based on Lutetium (Lu) like LYSO (Lu1.8Y.2SiO5:Ce) *has an high stopping power (high Z), high light yield and very short decay time (very fast signals).*

2,6% of the natural Lu is ^{176}**Lu**, *a radioisototope with a long half life decaying via two different beta decays followed by gamma emissions.*

1) How to use the i-Spector Digital

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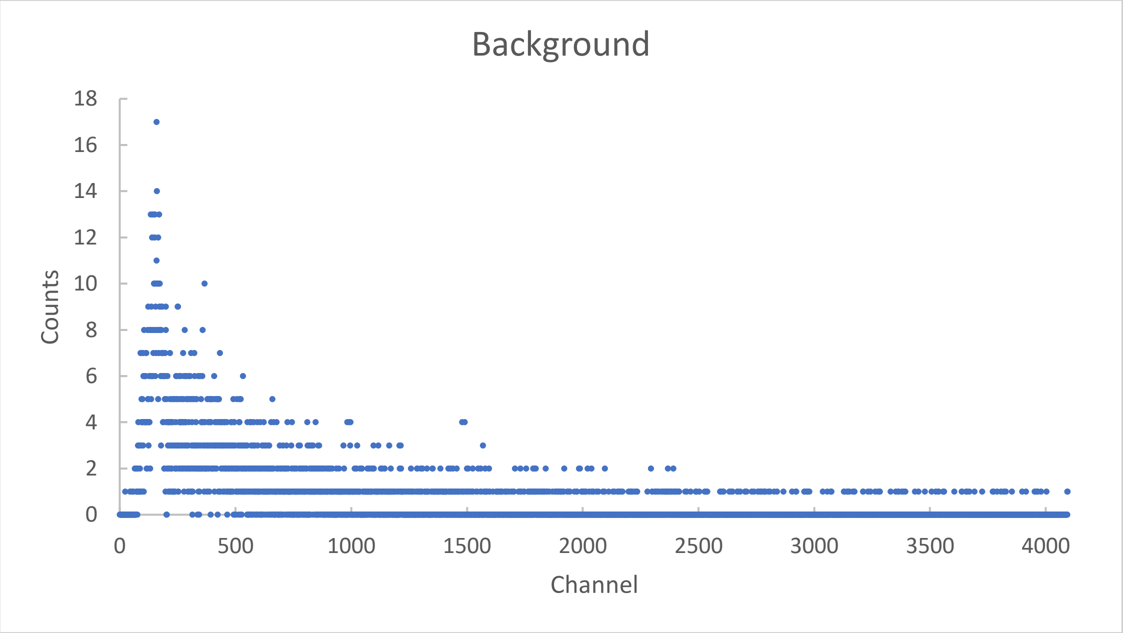

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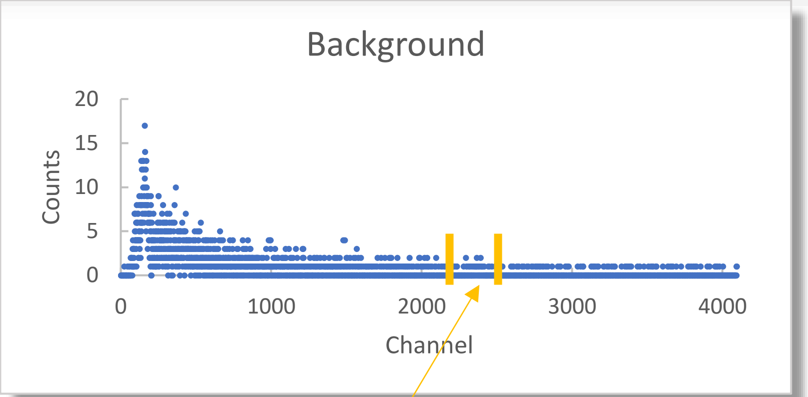
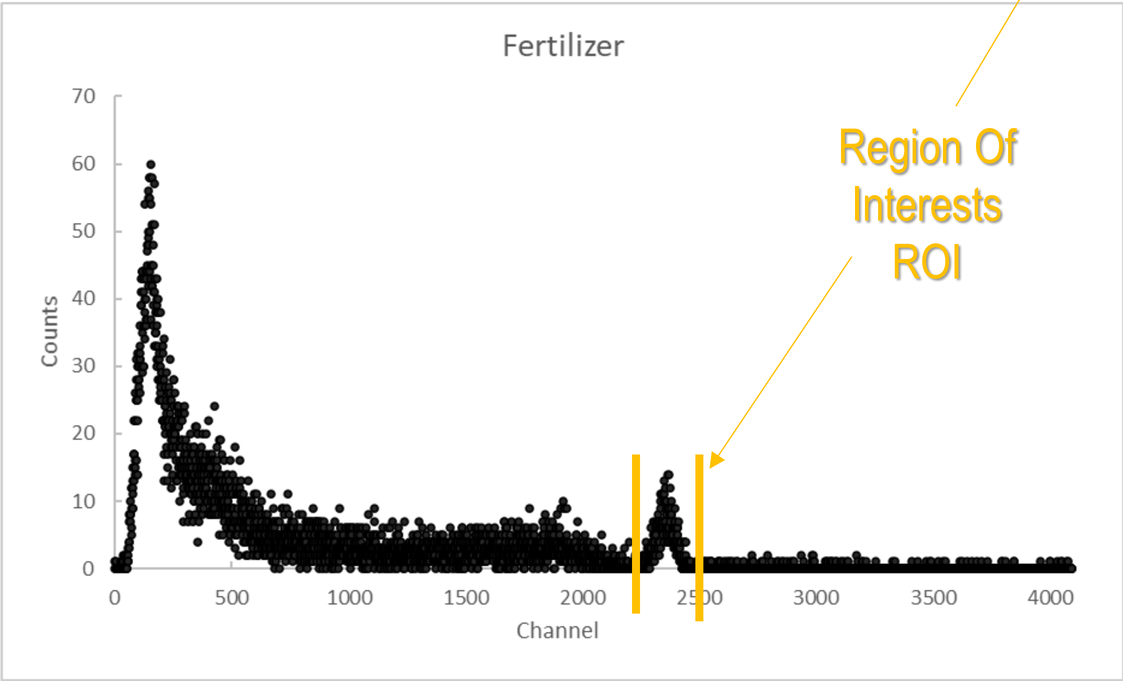
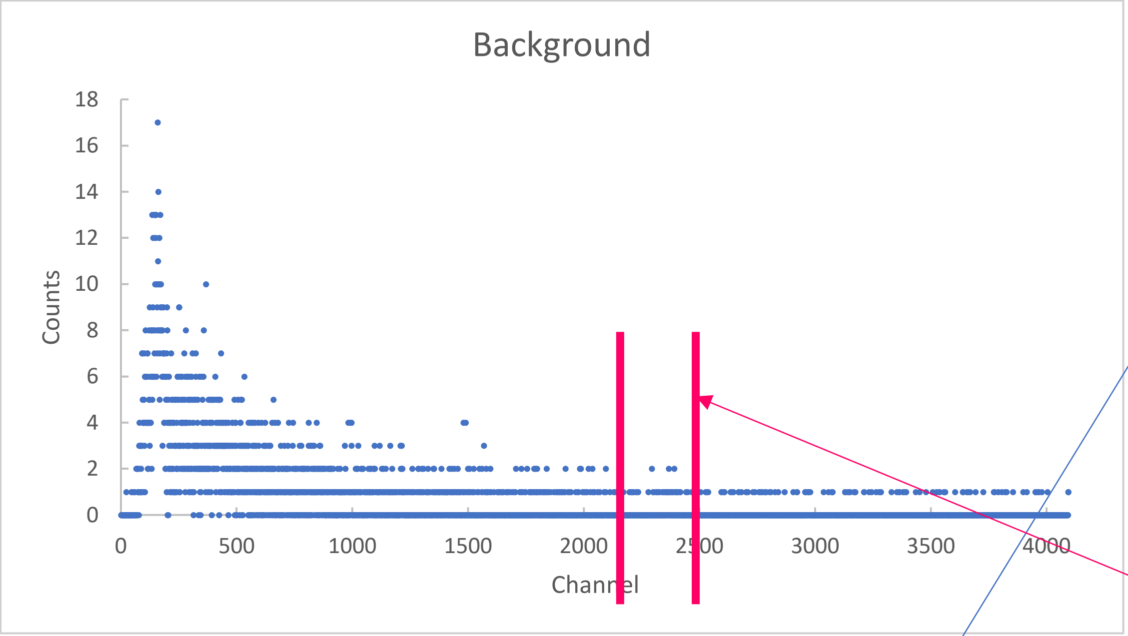




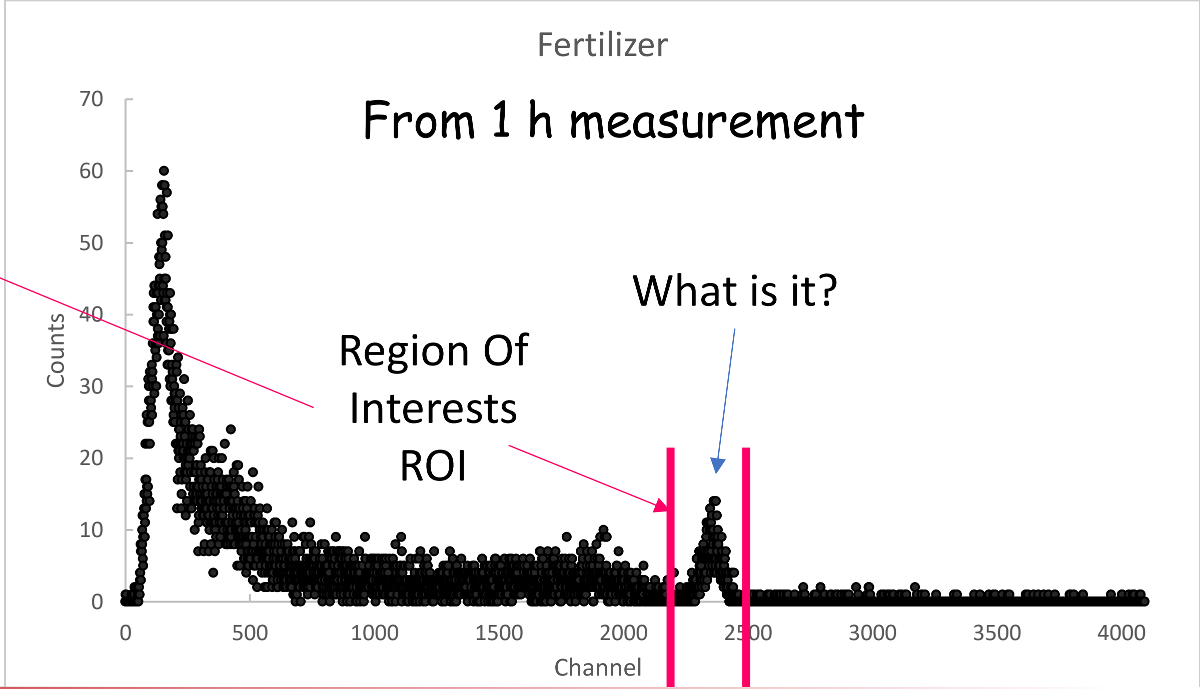
Fertilizer – Potassium Chloride



For our hands on take a 30 min spectra with the Potassium Chloride sample

Lead shielding to reduce environmental background

Fertilizer



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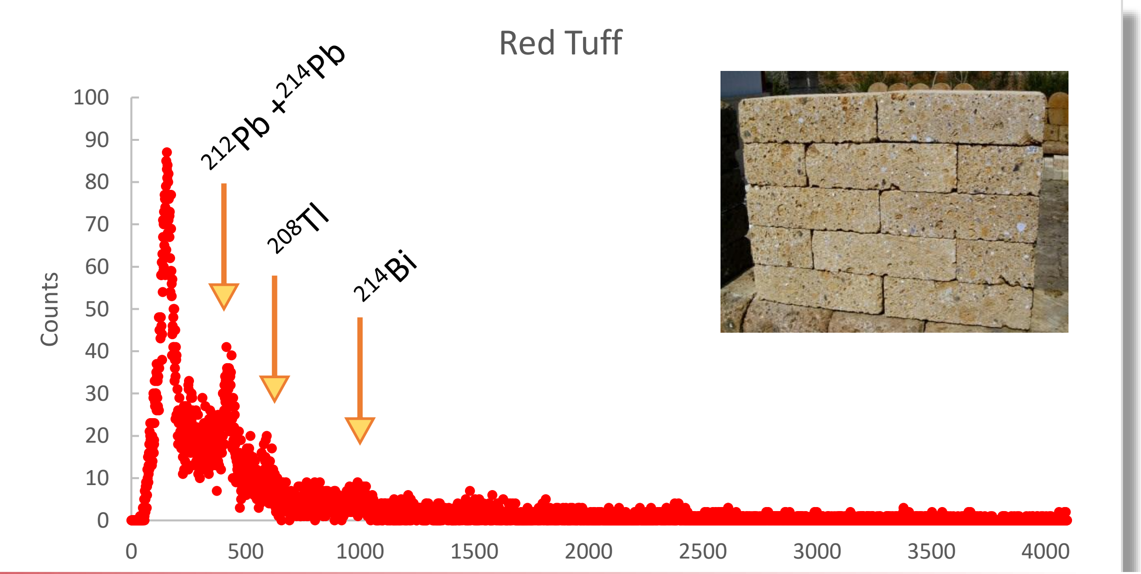
U-238

99.98% 0.02%		
Pb214	26.8 minutes	53.2 (1.1%) 242.0 (7.46%) 295.2 (19.2%) 351.9 (37.1%) 785.9 (1.09%)
At218	2 seconds	-----
Bi214	19.7 minutes	609.3 (46.1%) 768.4 (4.89%) 806.2 (1.23%) 934.1 (3.16%) 1120.3 (15.0%) 1238.1 (5.92%) 1377.7 (4.02%) 1408.0 (2.48%) 1509.2 (2.19%) 1764.5 (15.9%)

Th-232

Bi212	60.6 minutes	39.9 (1.1%) 727.3 (6.65%)
64.06% 35.94%		
Po212	304 nsec	--------
Tl208	3.1 minutes	277.4 (6.31%) 510.77 (22.6%) 583.2 (84.5%) 763.1 (1.81%) 860.6 (12.4%)



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Thorium Lantern Mantle

Uranium Glazed Pottery

Rare earth uranium oxide

Decades-Old Lenses

Uranium glass beads

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3) Background measurement (time run = 30’)
4) Calibration verification and tuning with Pot
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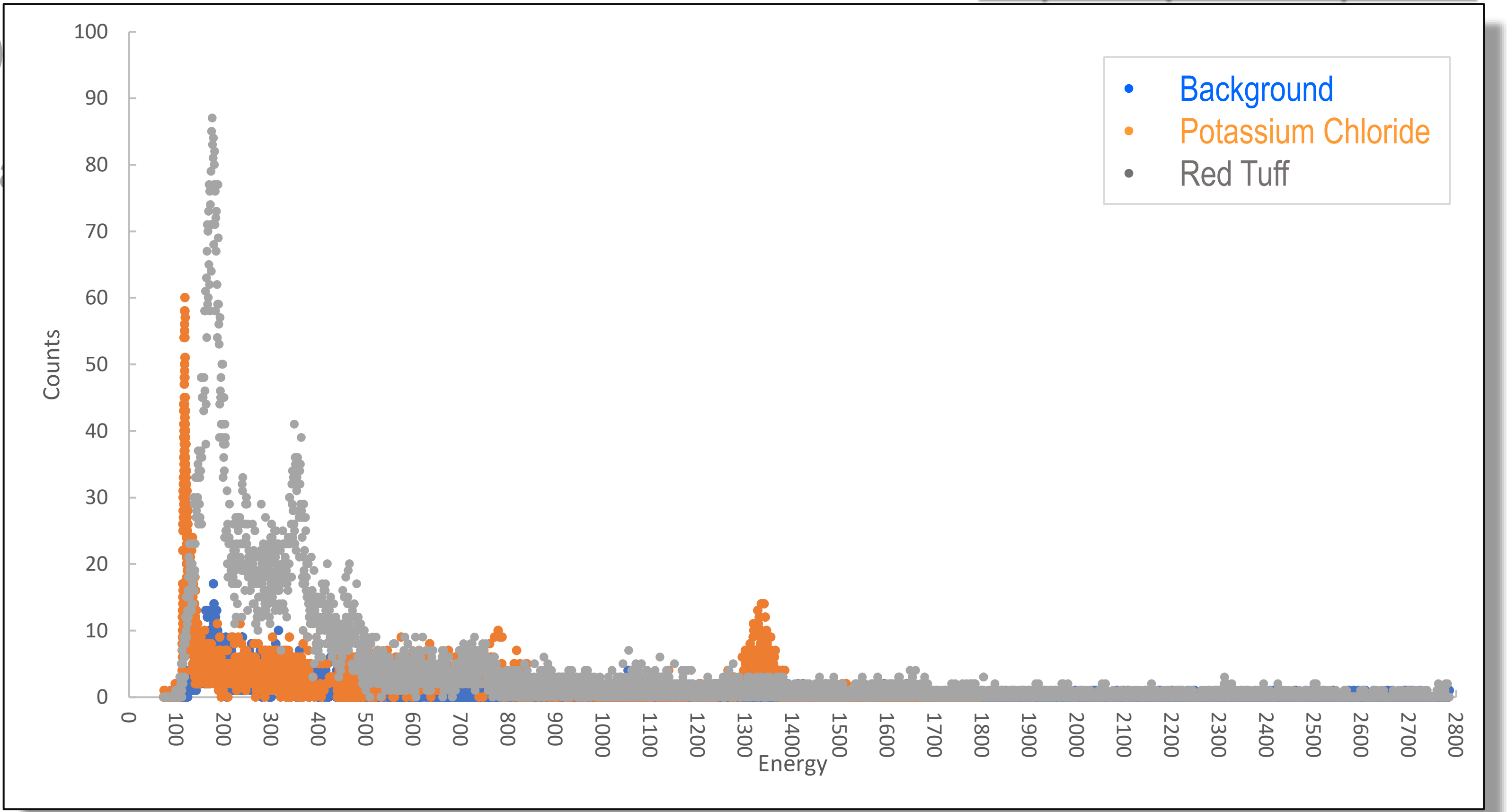
6) Test sample radiation identification
7) **Analysis of spectra and superposition**
8) Passive Radon Measurements

Superimposed spectra



1) How to use the i-Spector Digital

2) Energy calibration of the system based on

3) Background measurement (time run = 30')

4) Calibration verification and tuning with Pota

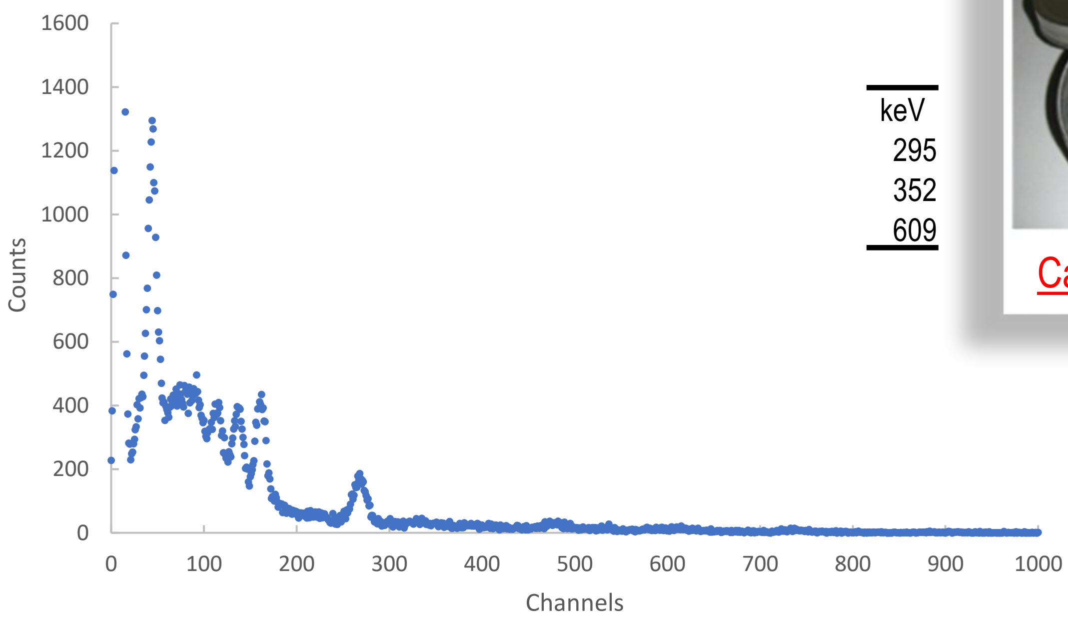
5) Rock sample Spectrum (time run = 30')

6) Test sample radiation identification

7) Analysis of spectra and superposition

8) Passive Radon Measurements (time run=60')

Measurement of the adsorbed radon activity



keV
295
352
609

Canisters of Activated Carbon

The amount of adsorbed radon by the canisters can be evaluated via the detection of the gamma rays emitted by the ^{214}Pb e dal ^{214}Bi.
Among the many available gamma emissions, the following nuclei are used as they are formed in a short time from the decay of Radon:

- 295 keV and 352 keV from ^{214}Pb
- 609 keV from ^{214}Bi

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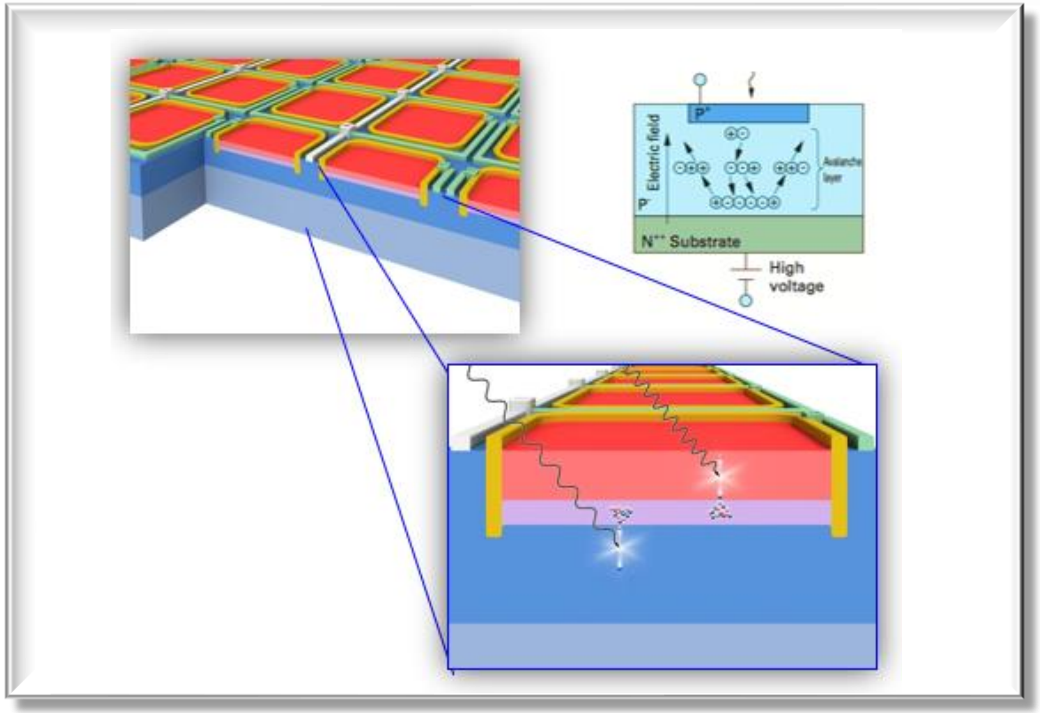
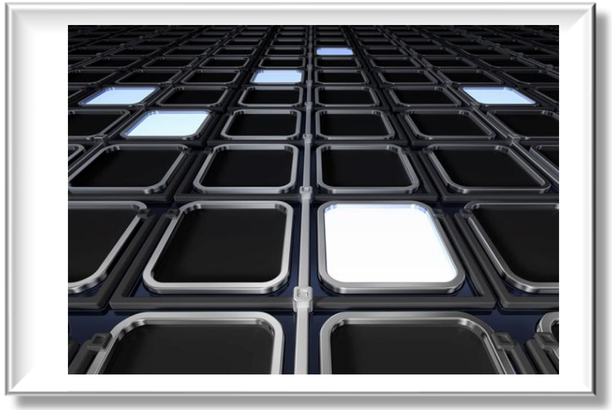


- SiPM is a High density (up to 10^4/mm2) matrix of diodes with a common output, working in Geiger-Müller regime
- Common bias is applied to all cells (few % over breakdown voltage)
- Each cell has its own quenching resistor (from 100kΩto several MΩ)
- When a cell is fired an avalanche starts with a multiplicative factor of about 10^5-10^6
- The output is a fast signal (t_{rise}~ ns; t_{fall} ~ 50 ns) sum of signals produced by individual cells
- SiPM works as an analog photon detector

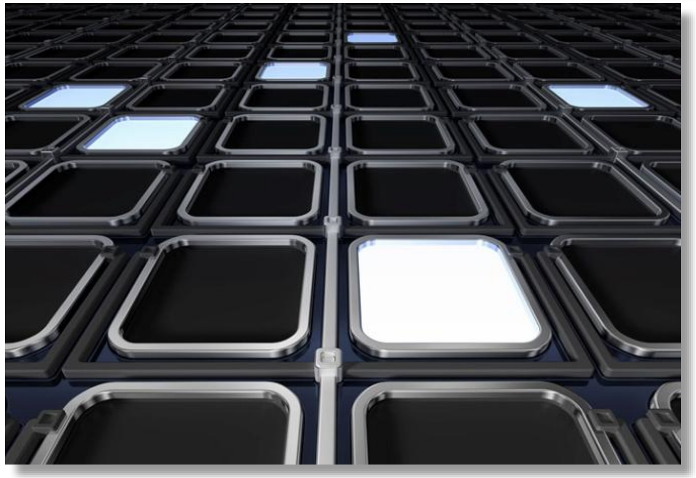
$$A_i \sim C\,(V_{breakdown} - V_{bias})$$

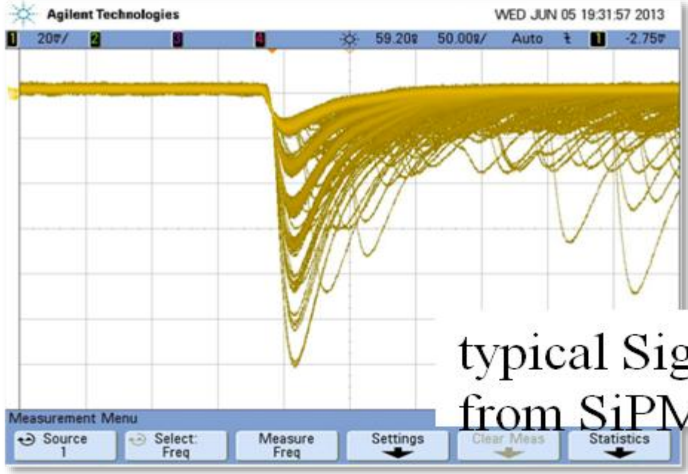
$$A = \Sigma A_i$$

- SiPM may be seen as a collection of binary cells, fired when a photon in absorbed
- "counting" cells provides an information about the intensity of the incoming light

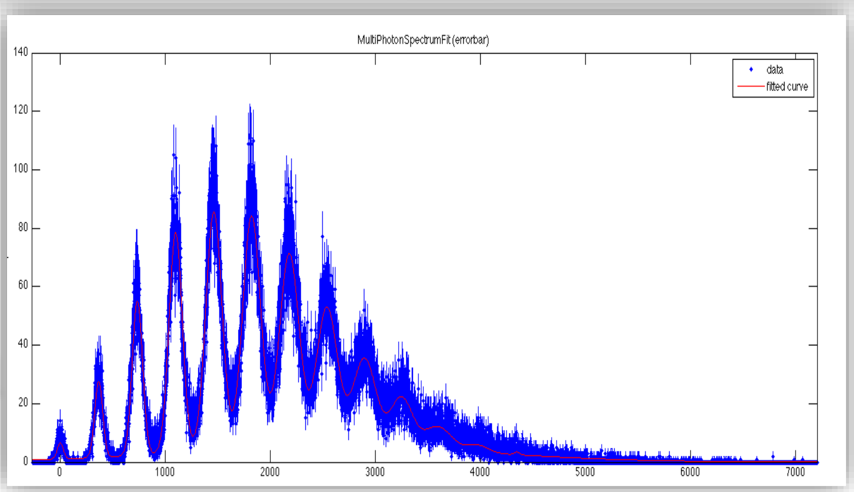


The high uniformity of pixel structure guarantees no avalanche fluctuations



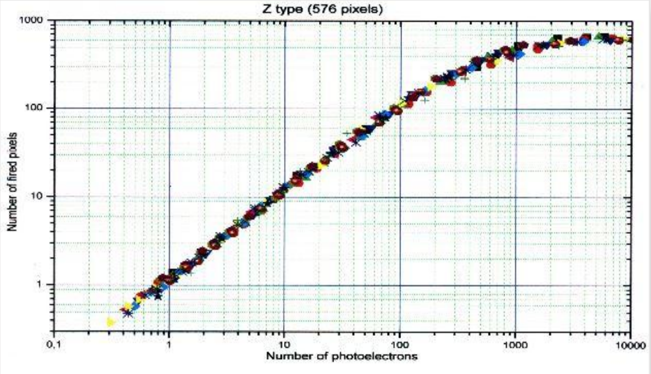


typical Signal from SiPM



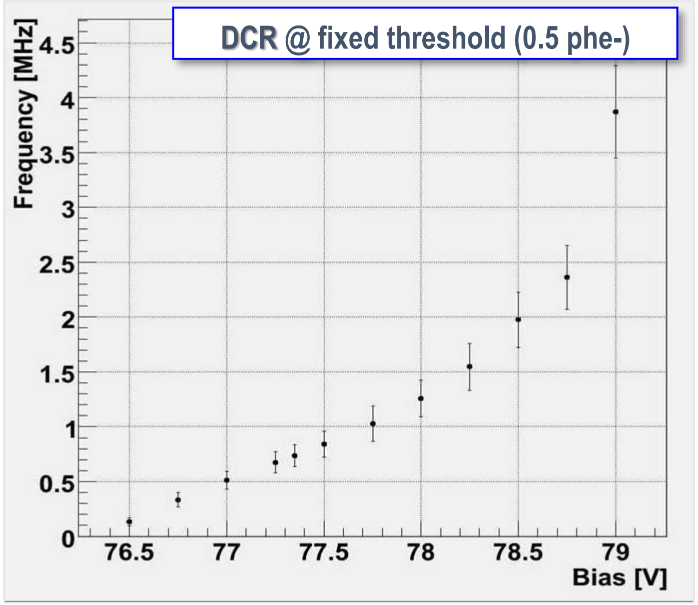
Linear response if the average number of photoelectrons/pixel is less than one

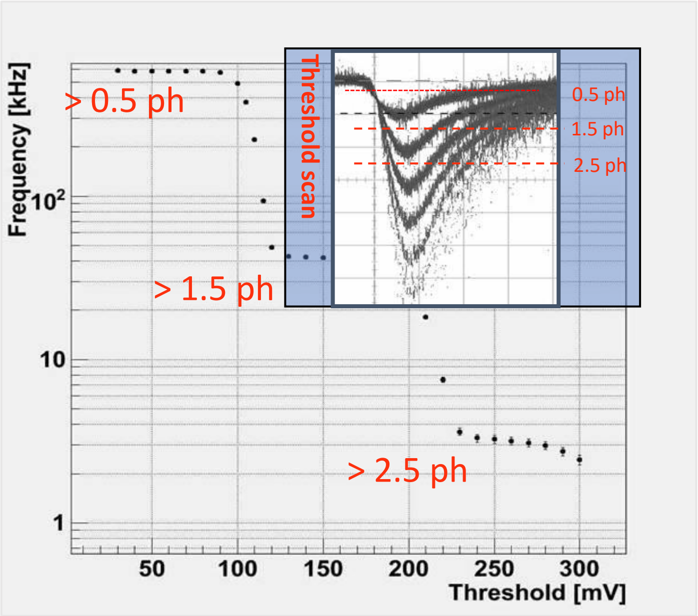
Number of pixel determines the SiPM **dynamic range**



Excellent Resolution

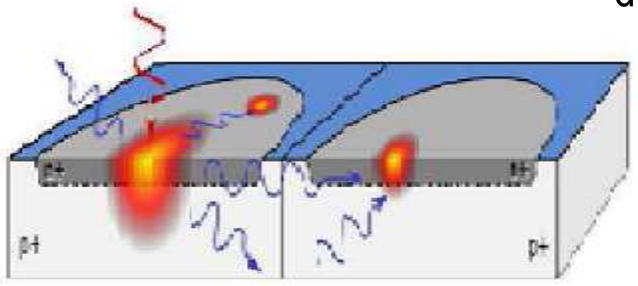
The **Dark Counts** (**DCR**) measure the rate at which a Geiger avalanche is randomly initiated by thermal emission.





Decrease DCR:

- lowering temperature
- lowering active volume – decrease V_{bias}
  – small area



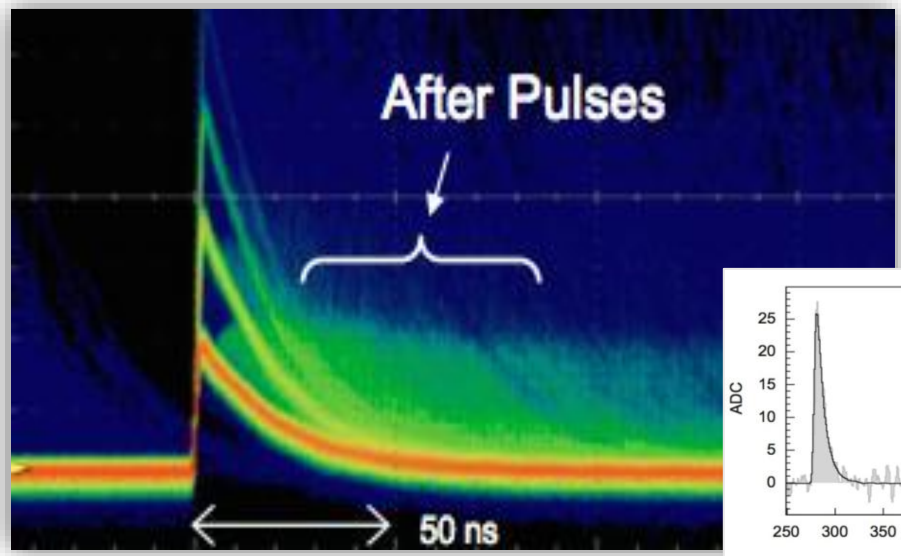
An avalanche generation can fire another cell by a photon; measuring the DCR for different thresholds is possible to define and evaluate the **Optical Cross Talk** (**OCT**) as:

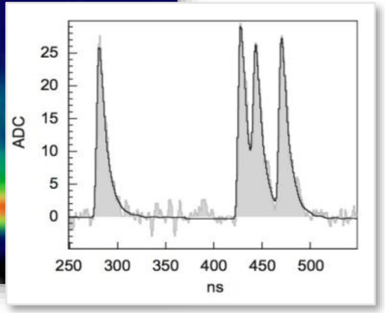
Decrease OCT:

- low gain/V_{bias}
- big pixel size
- trench for optical isolation

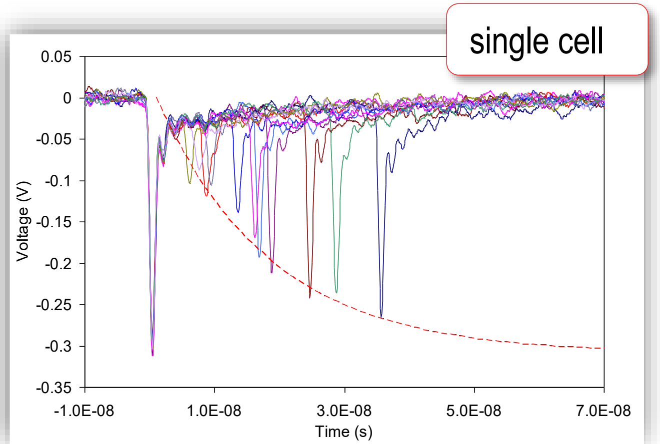
$$X_{talk} = \frac{DCR(1.5\,ph)}{DCR(0.5\,ph)}$$

After Pulse: It is a delayed avalanches triggered by the release of a charge carrier that has been produced in the original avalanche and has been trapped on an impurity





- Limiting the photon counting resolution
  - The release of the trapped carriers is characterizated by a typical decay time ~200 ns



The pulse amplitude depends on the pixel recovery state

$$\xi(\Delta t) = 1 - exp(-\Delta t/\tau_r)$$

Decrease AP:

- low V_{bias}
- small pixel

Quanto sono radioattive le rocce?

Granite (intrusive igneous rock)

~1000 Bq/kg

Tuff (magmatic rock)

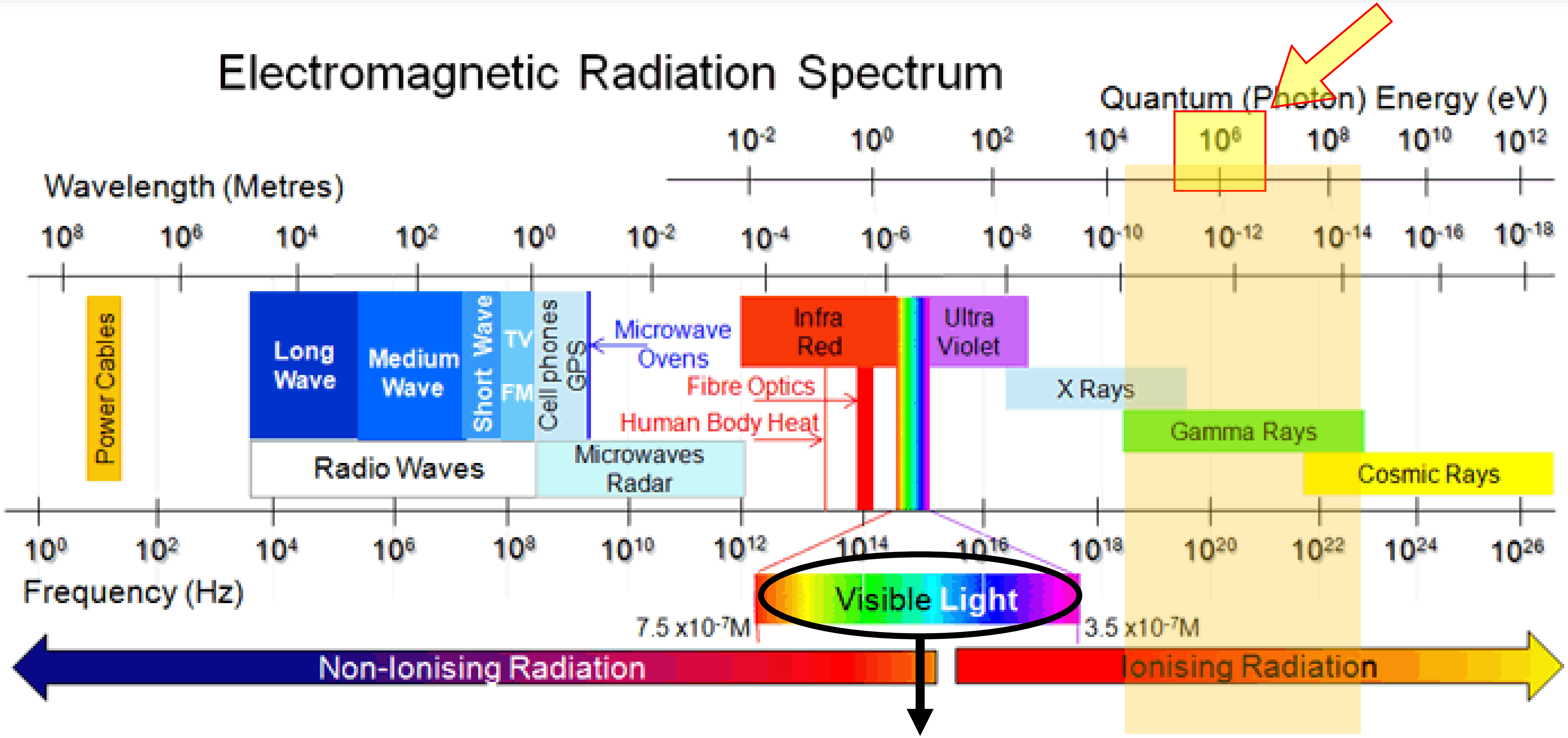
~1800 Bq/kg

Marble (limestone rock)

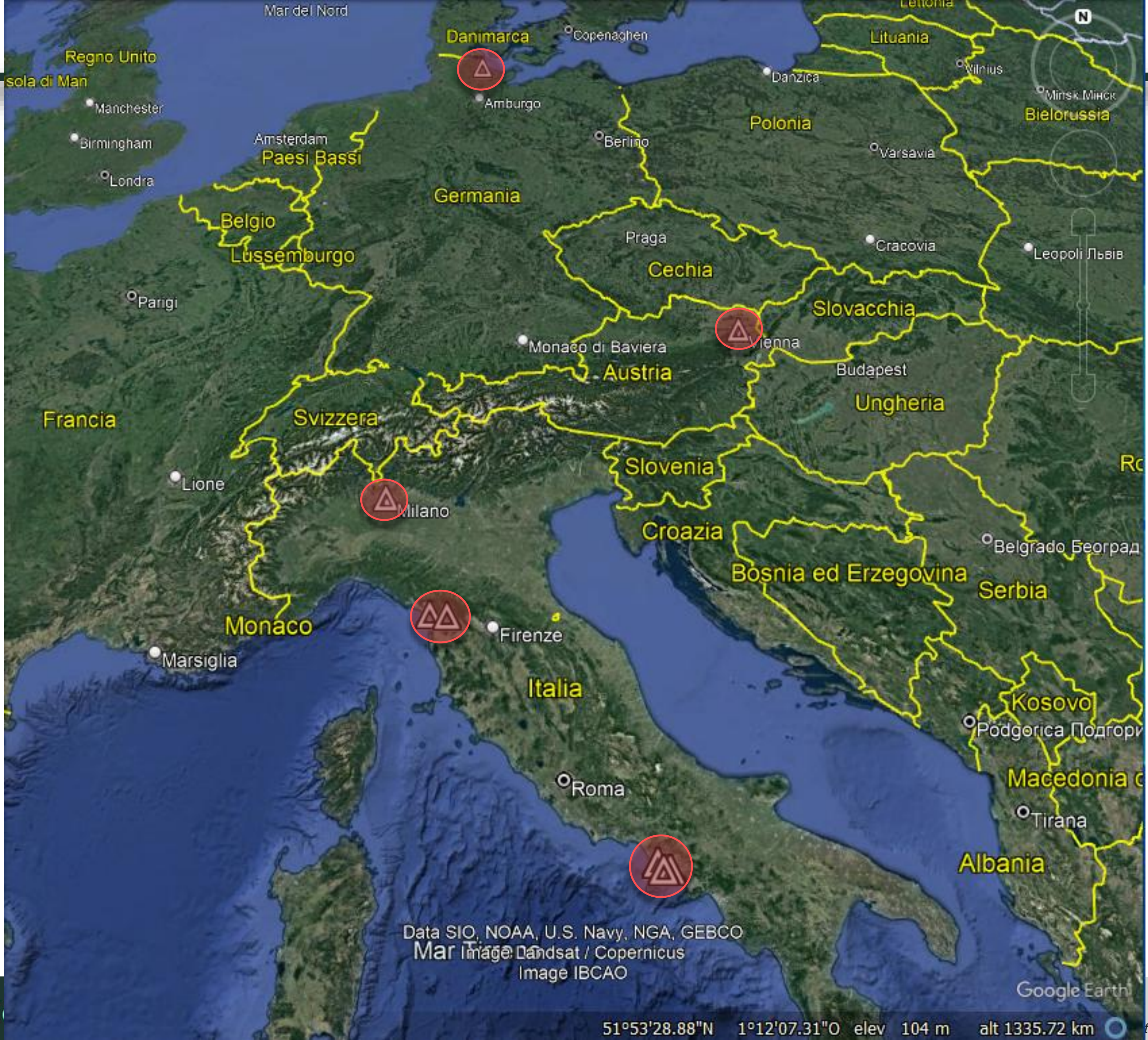
~100 Bq/kg

Gypsum (sedimentary rock)

~100 Bq/kg



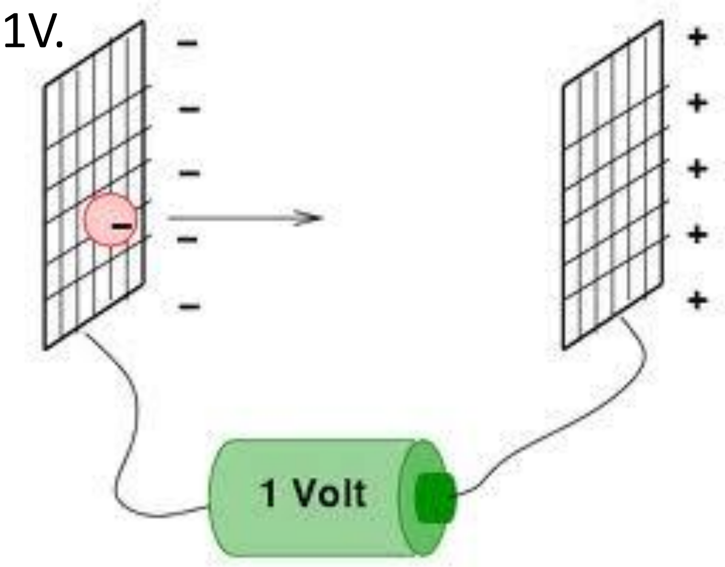
The human eye can see light radiation
from ~370 nm and ~700 nm


Mar del Nord
Danimarca
Copenaghen
Lituania
Regno Unito
Isola di Man
Amburgo
Danzica
Vilnius
Minsk Минск
Bielorussia
Manchester
Birmingham
Amsterdam
Paesi Bassi
Berlino
Polonia
Varsavia
Londra
Germania
Belgio
Lussemburgo
Praga
Cechia
Cracovia
Leopoli Львів
Parigi
Slovacchia
Monaco di Baviera
Vienna
Budapest
Austria
Ungheria
Francia
Svizzera
Slovenia
Lione
Milano
Croazia
Belgrado Београд
Bosnia ed Erzegovina
Serbia
Monaco
Firenze
Marsiglia
Italia
Kosovo
Podgorica
Macedonia
Roma
Tirana
Albania
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Image IBCAO
Google Earth
51°53'28.88"N 1°12'07.31"O elev 104 m alt 1335.72 km

Il MeV: una grandezza conveniente per misurare le energie dei decadimenti radioattivi

Comunemente viene usato il Joule (J) come unità di misura per misurare l'energia. Durante i processi di decadimento **l'energia rilasciata è trasportata dalle particelle è tipicamente dell'ordine di grandezza di 10^{-13}J**.

E' comodo introdurre una unità di energia chiamata elettro-volt (eV) definita come l'energia guadagnata da un elettrone che attraversa una differenza di potenziale 1V.



$$1eV = 1.6 \times 10^{-19}\ C \times 1\ V = 1.6 \times 10^{-19}\ Joule$$

ossia, anche

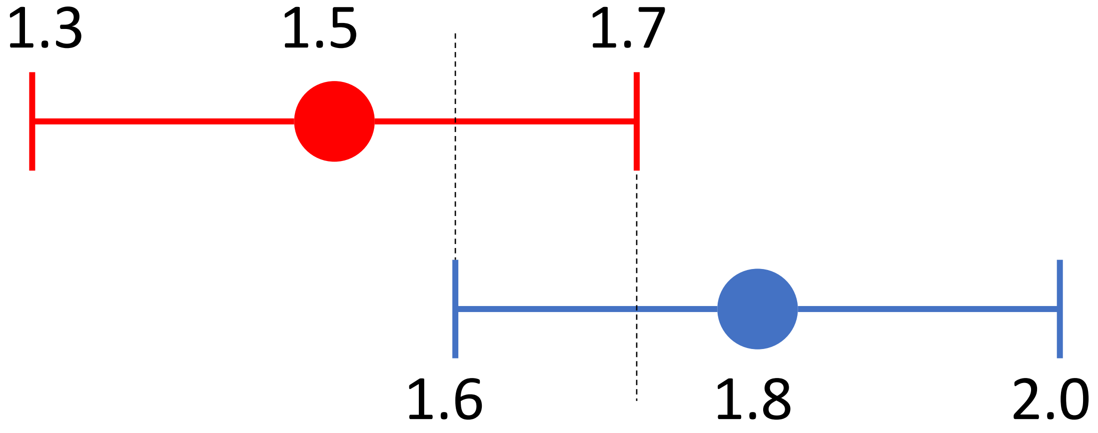
$$1\ Joule = 0.6 \times 10^{19}\ eV$$

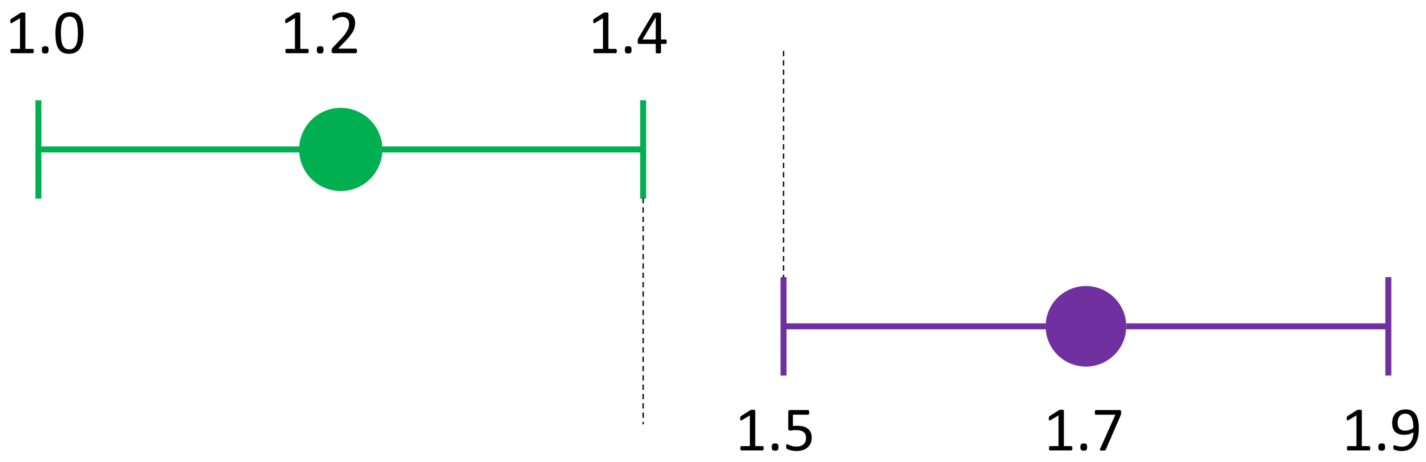
Nei processi nucleari le energie in gioco, dell'ordine di 10^{-13} J, sono dunque dell'ordine di

1 MeV (mega elettro-volt) = 10^6 eV

Cosa significa che due misure sono compatibili?

Per confrontare due misure della stessa grandezza (in questo caso le abbondanze di U, Th e K) occorre confrontare gli intervalli di confidenza. Le due misure si dicono compatibili se i rispettivi intervalli di incertezza hanno intersezione non nulla.





$aK[\%]_1 = 1.5 \pm 0.2$ e $aK[\%]_2 = 1.8 \pm 0.2$

$aK[\%]_3 = 1.2 \pm 0.2$ e $aK[\%]_4 = 1.7 \pm 0.2$

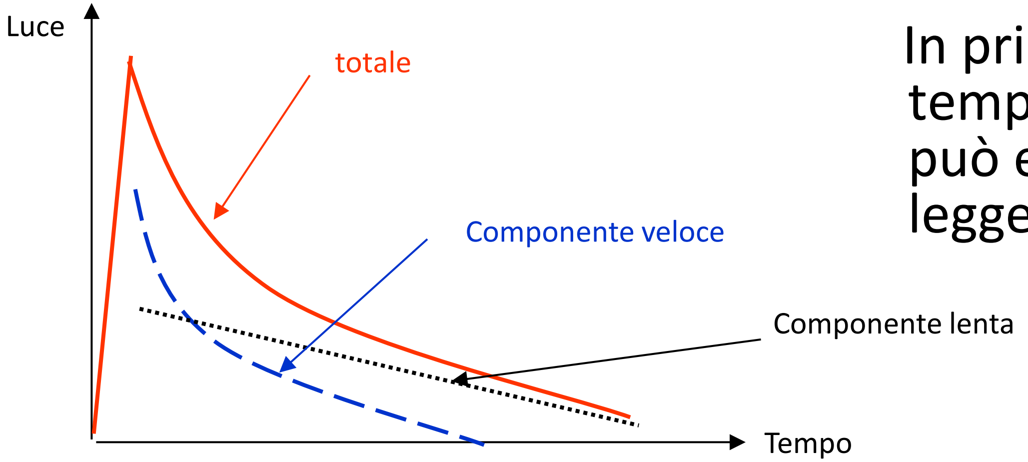
Compatibili

Non compatibili

Luminescenza: Materiali luminescenti assorbono energia e la riemettono sotto forma di luce visibile.

Fluorescenza: l'emissione avviene subito dopo l'assorbimento (10^{-8} s).

Fosforescenza: l'emissione è ritardata (lo stato eccitato è metastabile). In questo caso il tempo fra l'assorbimento e la riemissione può durare dai μs alle ore (dipende dal materiale).



In prima approssimazione l'evoluzione temporale del processo di riemissione può essere descritto da una semplice legge esponenziale:

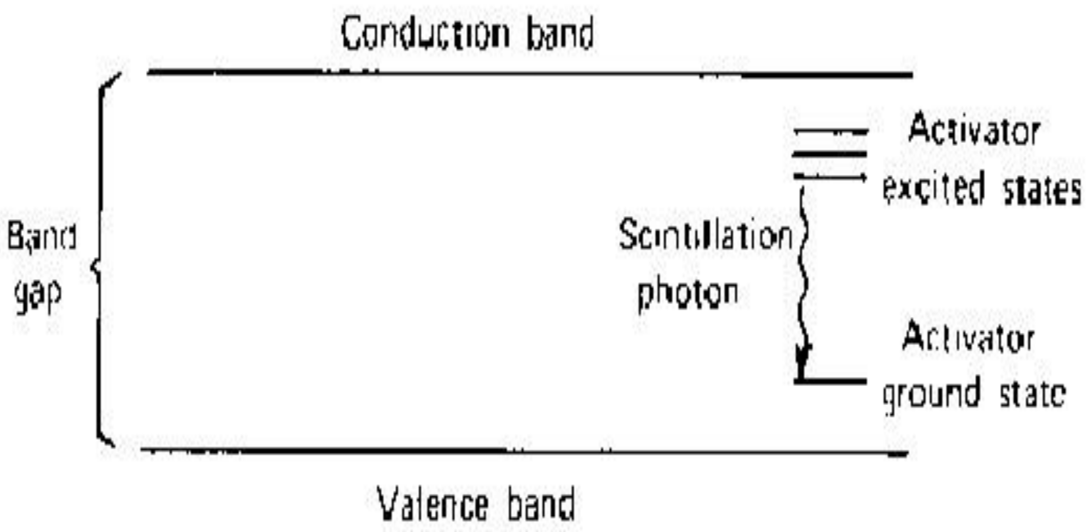
$$N = \frac{N_0}{\tau_d} \cdot e^{-t/\tau_d}$$

Dove N è il numero di fotoni emessi al tempo t, t_d il tempo di decadimento ed N_0 il numero totale di fotoni emessi.

Il tempo di assorbimento dell'energia (eccitazione degli atomi e delle molecole) è in generale molto più breve del tempo di riemissione.

Scintillatori Inorganici

Il meccanismo di scintillazione negli scintillatori inorganici è caratteristico della struttura a bande elettroniche che si trovano nei cristalli.



Quando una particella entra in un cristallo possono accadere 2 processi:

i. si eccita un elettrone dalla banda di valenza in quella di conduzione, creando così un elettrone ed una lacuna liberi. (ionizzazione)

ii. si crea un eccitone spostando un elettrone dalla banda di valenza in quella degli eccitoni (posta appena al di sotto della banda di conduzione). In questo caso elettrone e lacuna rimangono legati, ma possono muoversi liberamente (in coppia) nel cristallo.(eccitazione)

Se il cristallo contiene delle impurità (sono necessarie), si possono creare localmente dei livelli elettronici nella banda delle energie proibite. Gli atomi di impurità sono chiamati centri attivatori.

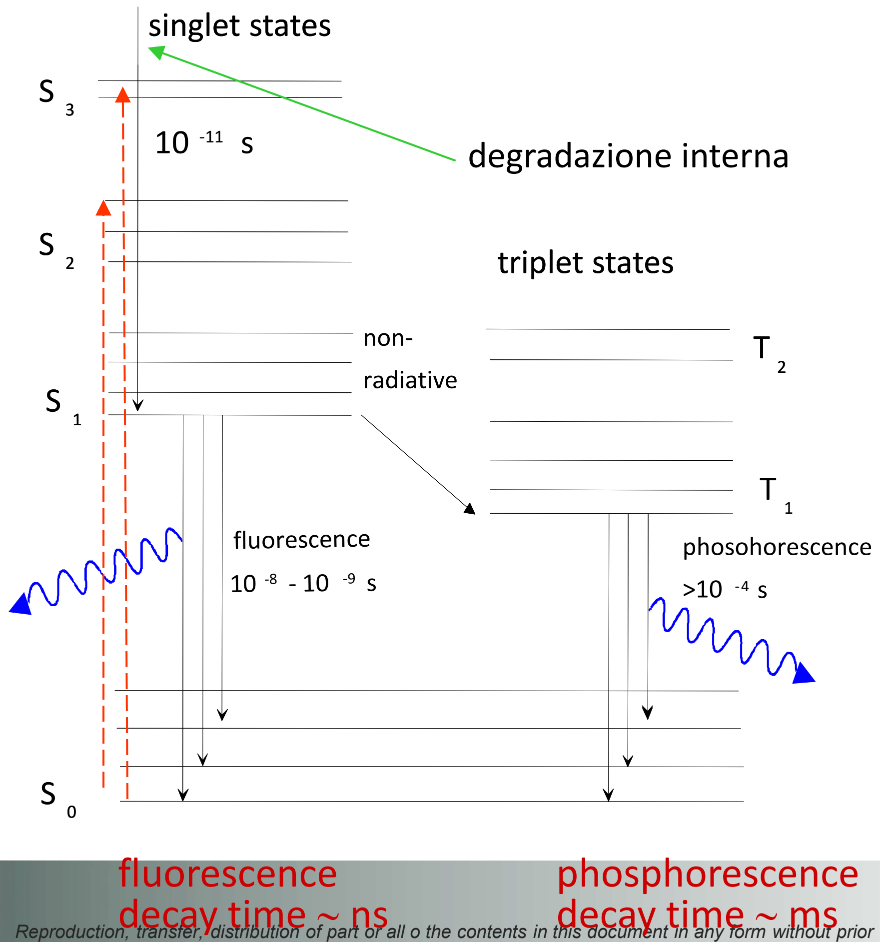
Se una lacuna libera od una lacuna di un eccitone incontra uno di questi centri attivatori, può ionizzare uno di questi atomi di impurità. Se ora arriva un altro elettrone, questo cade nel buco (lacuna) lasciato dalla ionizzazione precedente ➔ si emette luce (se tale modo di diseccitazione è permesso).

Scintillatori Organici

Gli scintillatori organici sono dei composti di idrocarburi. In questi composti la luce di scintillazione deriva da transizioni degli elettroni di valenza liberi delle molecole.

L'eccitazione verso stati di energia superiore a S_1 è seguita da una rapidissima transizione (nell'ordine del ps) non radiativa verso S_1. Da questo livello le molecole si diseccitano verso lo stato fondamentale S_0 o uno degli stati vibrazionali emettendo luce di fluorescenza.

Molecular states



Caratteristiche generali degli scintillatori

Cristalli alcalino-alogeno: NaI, CsI, BGO,BaF_2

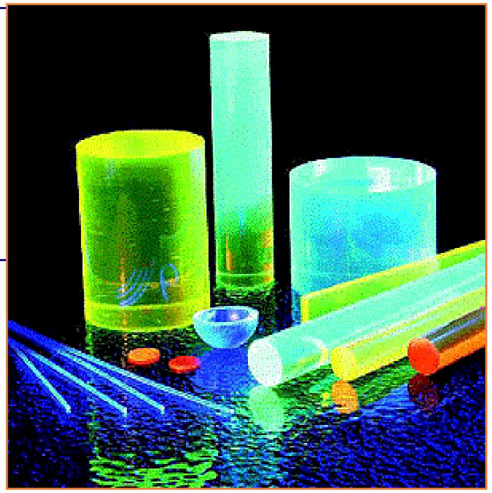
Buona linearità, lenti tempi di risposta

Spettroscopia gamma

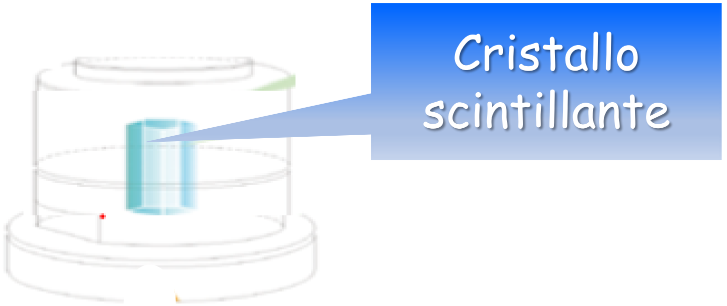
Scintillatori organici: antracene, stilbene

Buona velocità, bassa resa in luce

Spettroscopia beta e per neutroni veloci

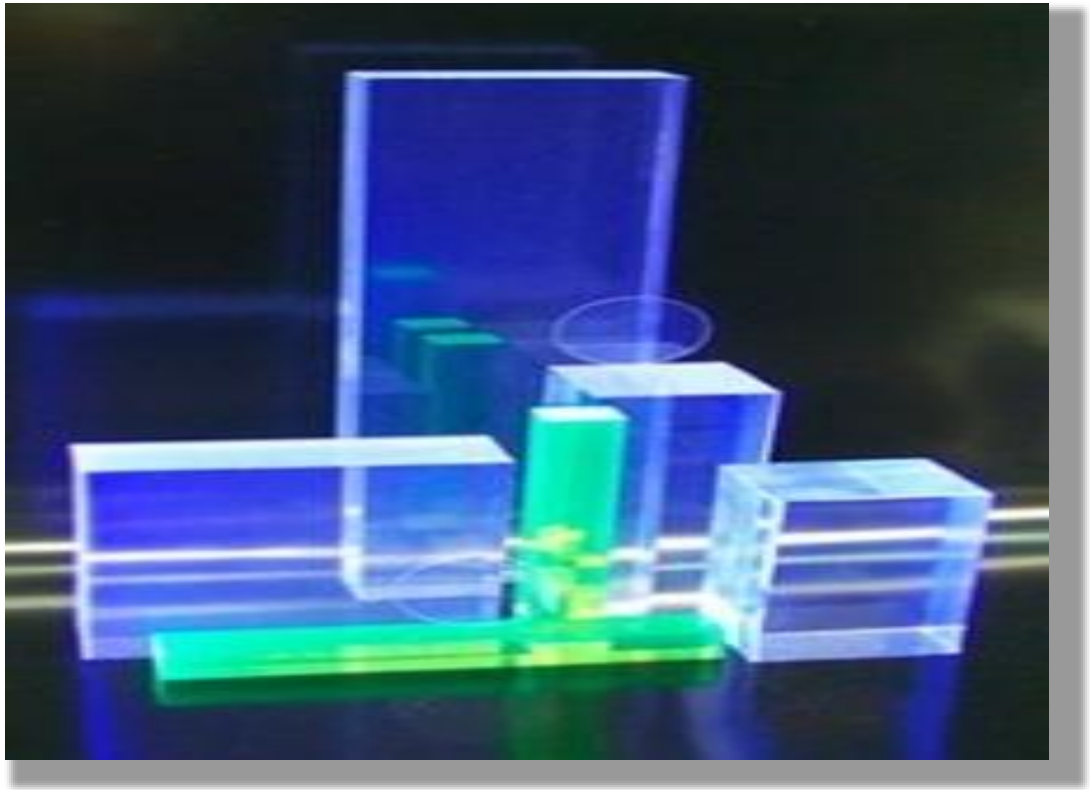


Scintillatore



A cosa servono gli scintillatori?

- A misurare l'energia ceduta
- A misurare il tempo di passaggio delle radiazioni



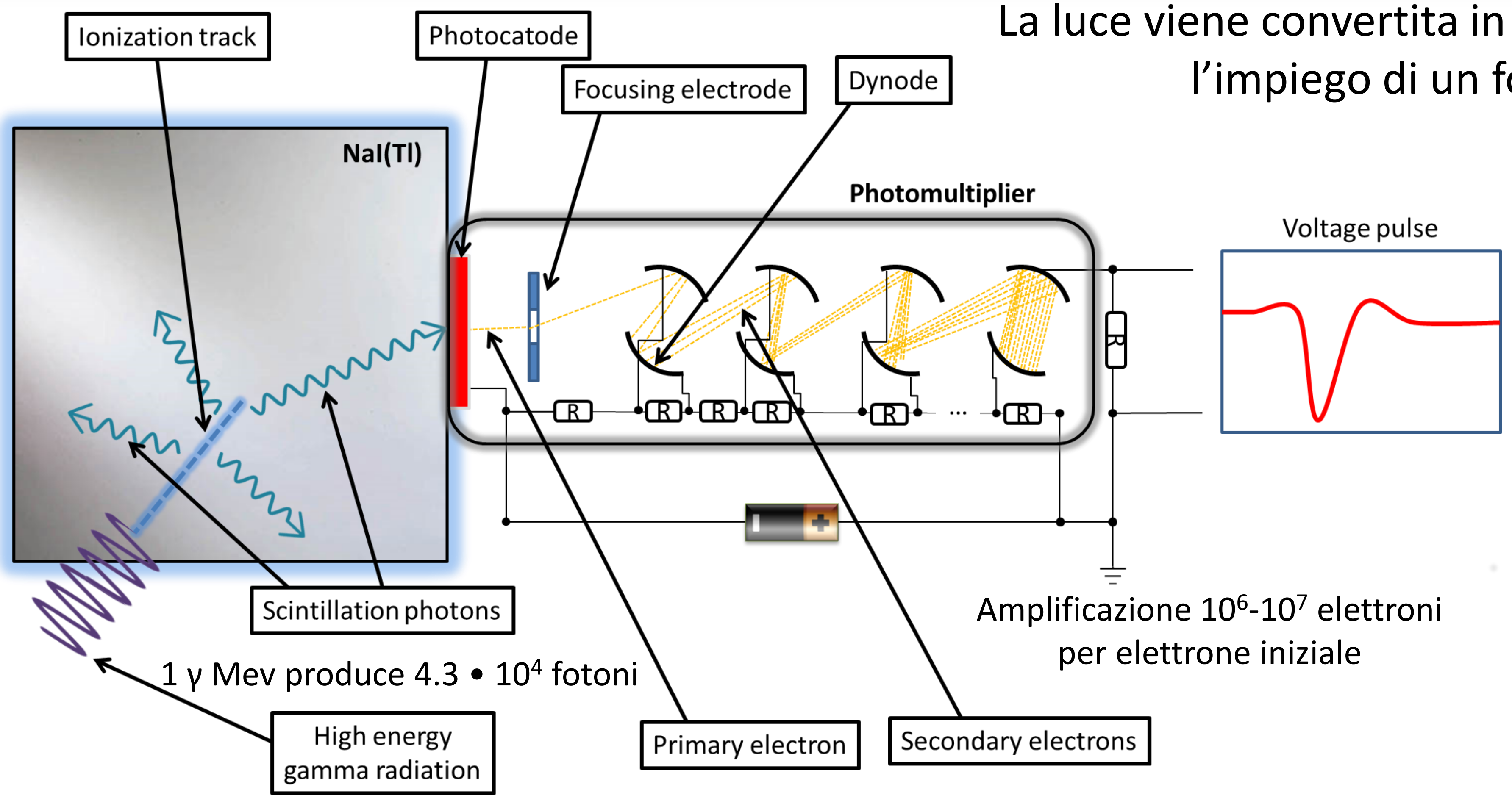
CsI(Tl)

Lo Ioduro di Cesio drogato al Tallio, CsI(Tl), è un materiale scintillatore che ha un'alta uscita in luce ed è relativamente lento. Il tempo di decadimento del cristallo, di circa 1100 ns.

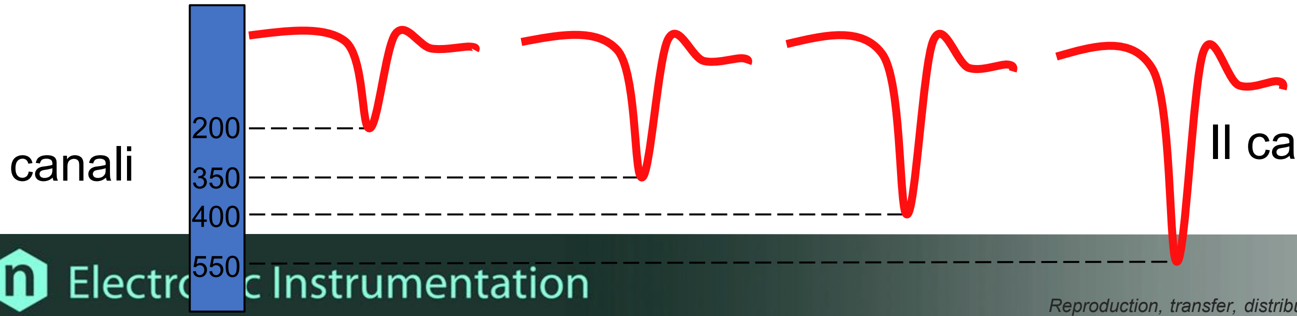
Densità	4.51 g/cm^3
Indice di rifrazione per l max	1.788
Punto di ebollizione	620 °C
Uscita in luce	95%
Costante di decadimento	1100 ns
l del max di emissione	580 nm
Principali applicazioni	rivelazione g, particelle pesanti

Dai fotoni alla corrente elettrica

La luce viene convertita in segnale elettrico mediante l'impiego di un fotomoltiplicatore



L'intensità dell'impulso di corrente in uscita è proporzionale all'energia del fotone incidente



Il canale di acquisizione è proporzionale all'energia dei fotoni incidenti