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Gamma Radiation: Regulation, Instrumentation and Detection

CAEN Winter School 2026

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Cristina Mattone

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Artificial radionuclides

From **bombs** or **Nuclear power plants** (ex. ^{137}Cs, actinides)

Very **long half lives**! Ex. Some nuclear waste goes to geological disposal.

Industrial (^{133m}Xe, ^{133}Ba, ^{241}Am) and **medical** (^{19}F, ^{67}Ga) radioistopes

Usually very **short half lives**, from hours to days, usually high activities!

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Radiation is a natural part of our environment!

Cosmic rays

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

Radionuclides from cosmic rays

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

Natural radionuclides [mean abundance]:

^{40}K	[2-2.5] %
$^{238,235}U$	[2-2.5] ppm
^{232}Th	[8-12] ppm

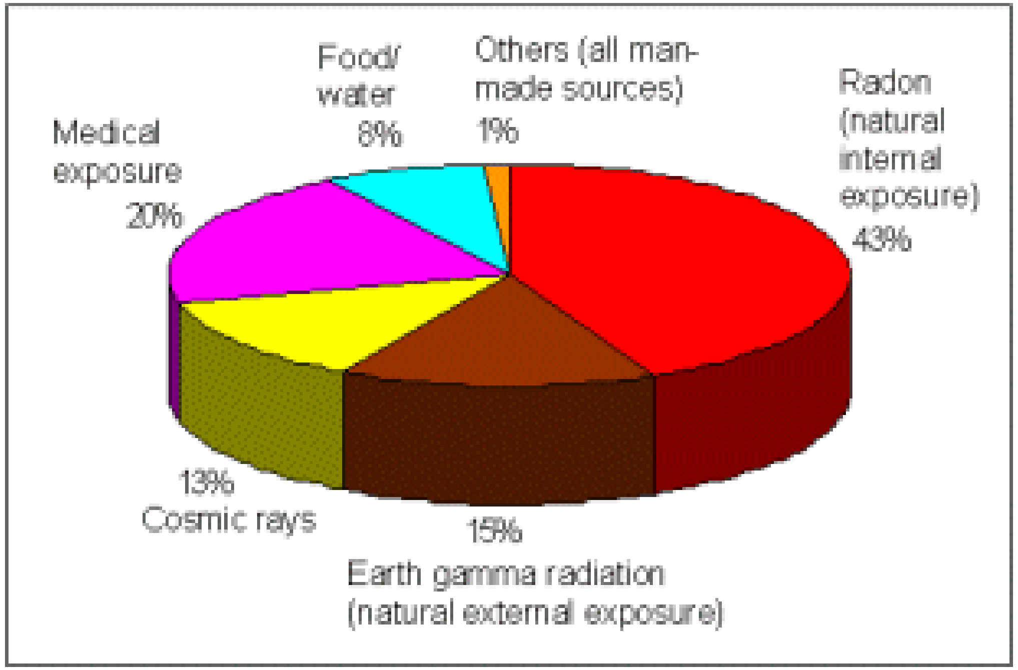
All has an half life $T_{1/2}$ > than the age of the solar system

Radiation is a natural part of our environment!

Radioactive sources:

- ***Natural***: **NORM** (**N**aturally **O**ccurring **R**adioactive **M**aterial), soil, water, air and food contribute to our exposure to ionizing radiation
- ***Cosmic rays***
- ***Industrial***: nuclear elements produced by industry
- ***Medicine***: nuclear medicine
- ***Military***

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

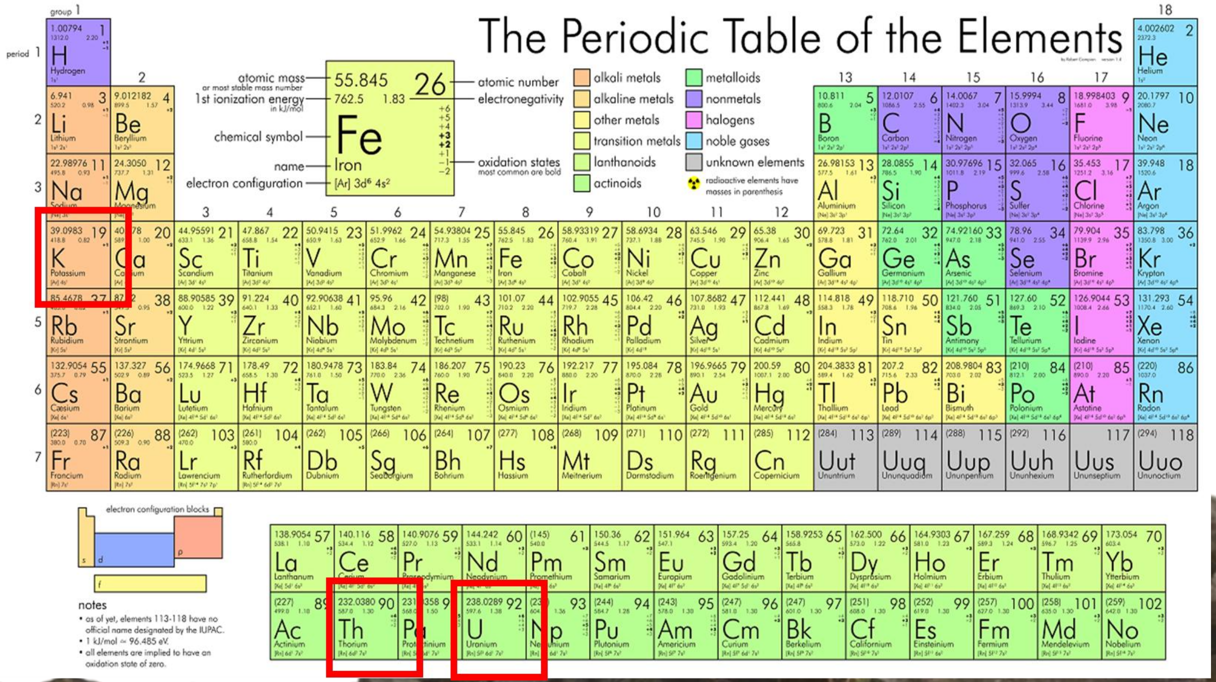


Natural gamma emitters

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

1 ton of rock

~2-3 g di U
~ 8-12 g di Th
~ 20-25 kg di K

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!

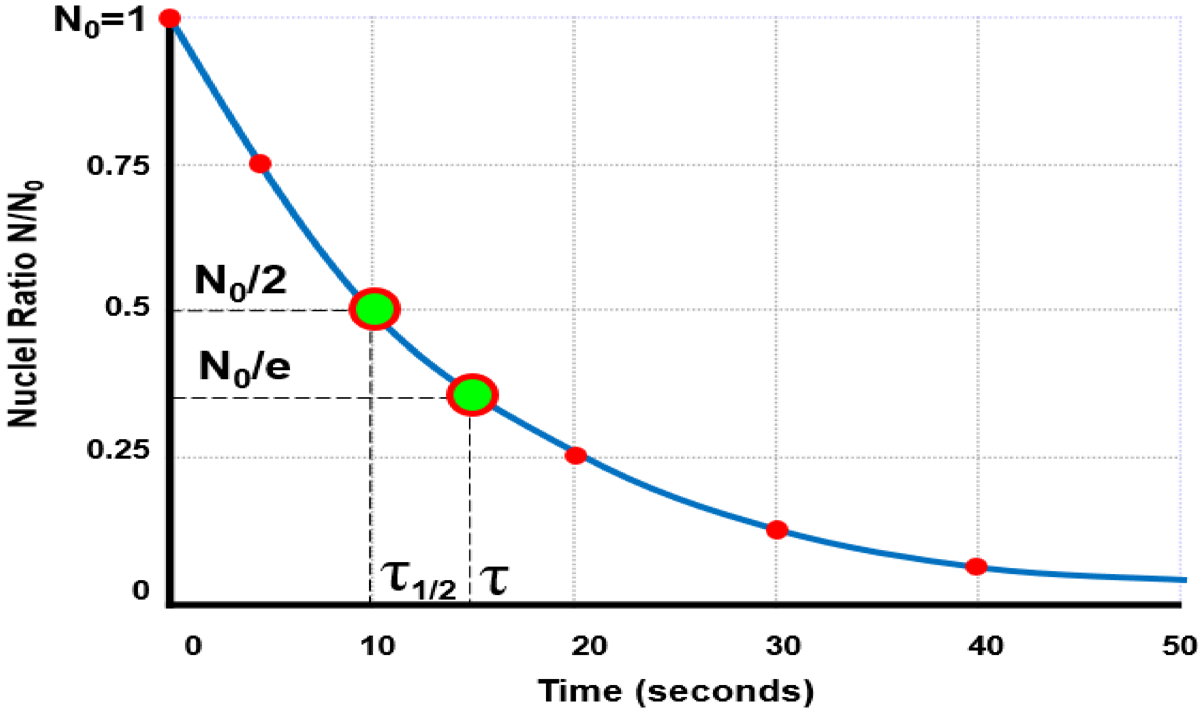
Pills:

$^{A}_{Z}X$ X = Element symbol

Z = Atomic Number (number of protons)

N = Neutronic number (number of neutrons)

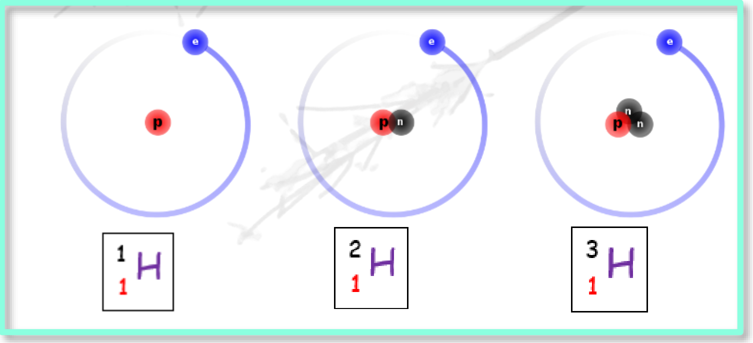
A = Mass Number (Z + N)



Isotopes

Elements with the same atomic number and different mass number!

Ex: Hydrogen isotopes



Activity:

The **activity** is defined as the number of decay for 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***: $t_{1/2} = \tau \lg 2 \approx 0,7\tau$

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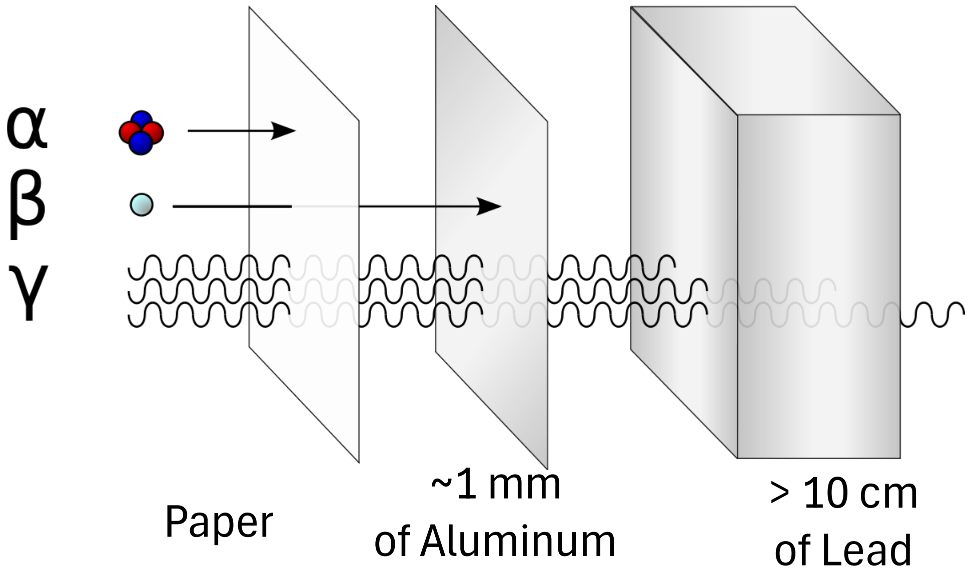
Radioactive decays

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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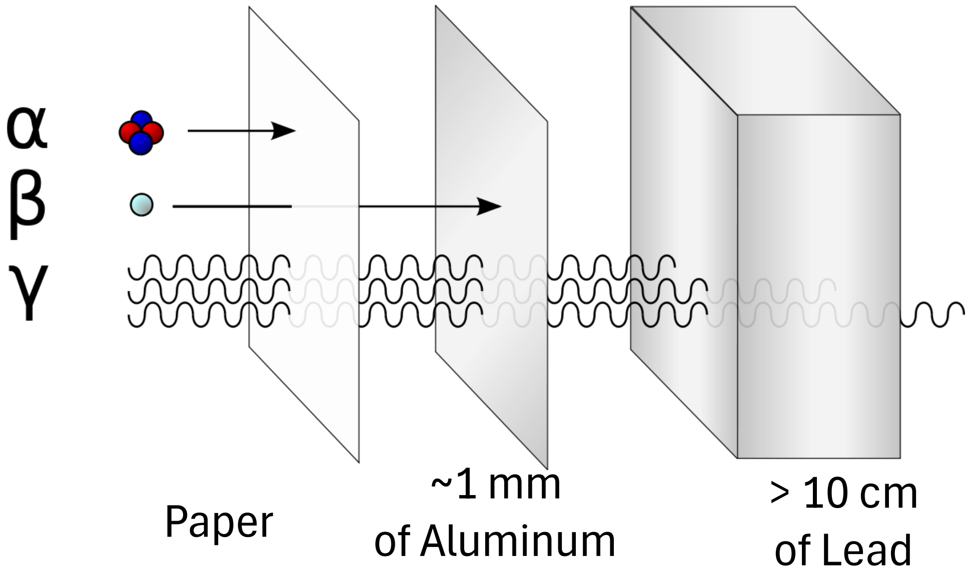

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Natural radioisotopes are primarily gamma emitters

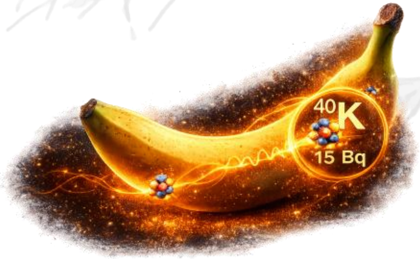
Usually, … decay is generated after an alpha or a beta decay which generate excited states. The excited states goes to a more stable state emitting photons and without changing state

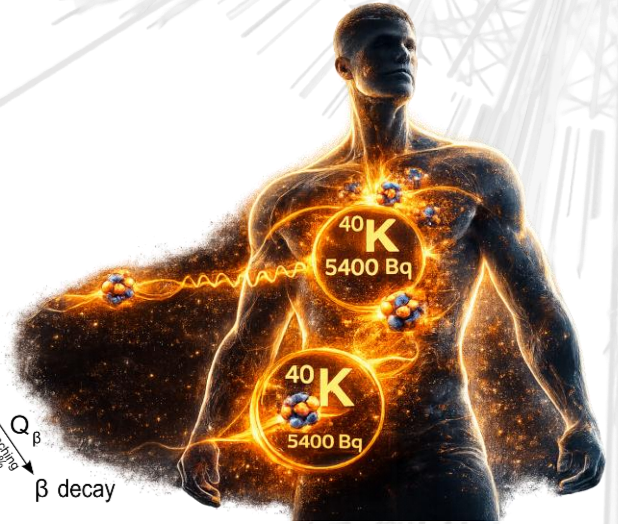
Potassium 40

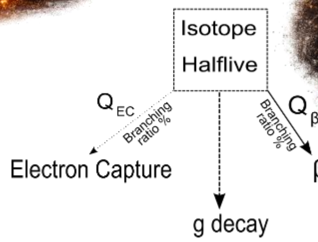
Potassium is essential for living. In the human body, most of the potassium is stored in the muscles. Potassium is also present in the soil, building materials, plants, animals and it is used in fertilizers.
In nature exists 3 potassium isotopes:

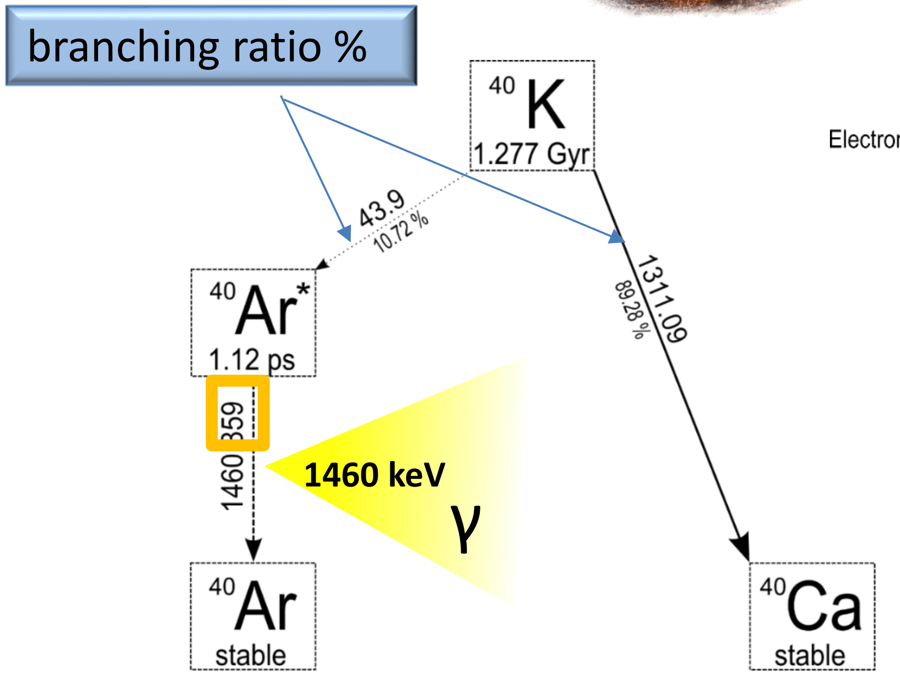
Type	^{39}K	^{40}K	^{41}K
n° protons	19	19	19
n° neutrons	20	21	19
Abundance (%)	93.26	0.01	6.73
$t_{1/2}$	Stable	$1.3\ 10^9$ y	stable

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



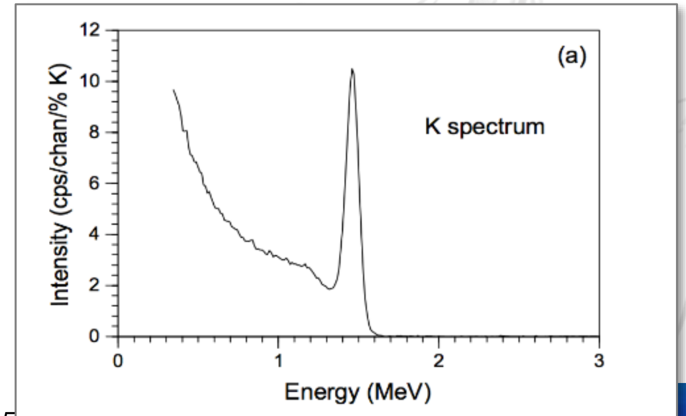






^{40}Ar decays emitting a gamma of 1460 keV (10%)

Measurement % -> 1% = 313 Bq/kg



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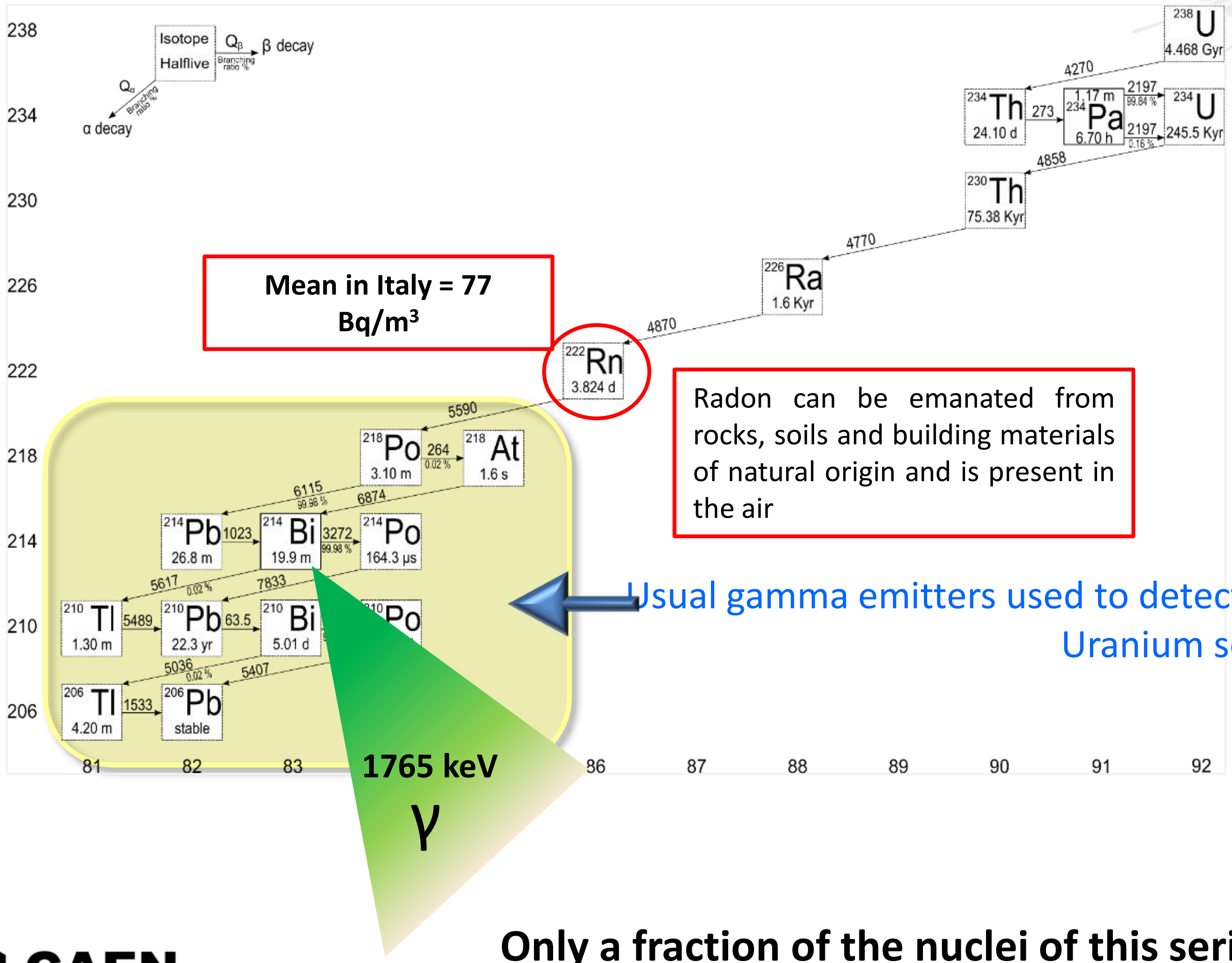
Uranium 238

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 miliard of years. The decay chain of an element down to its foundamental state is also called **radioactive series.**



Mean in Italy = 77 Bq/m³

Radon can be emanated from rocks, soils and building materials of natural origin and is present in the air

Usual gamma emitters used to detect the Uranium 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

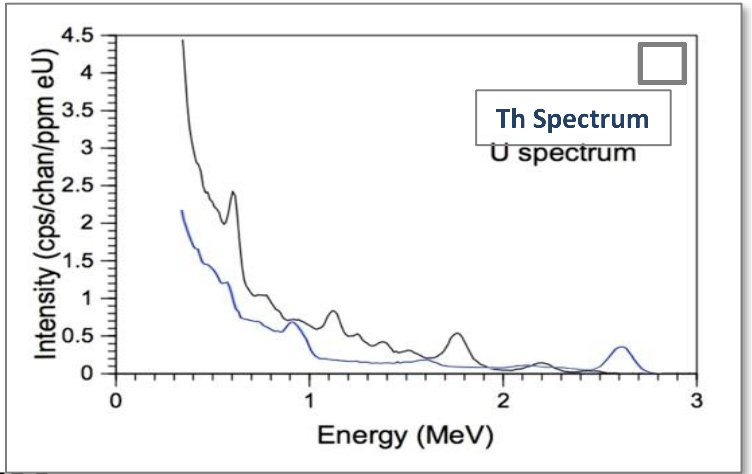
Only a fraction of the nuclei of this serie emits gamma radiation!

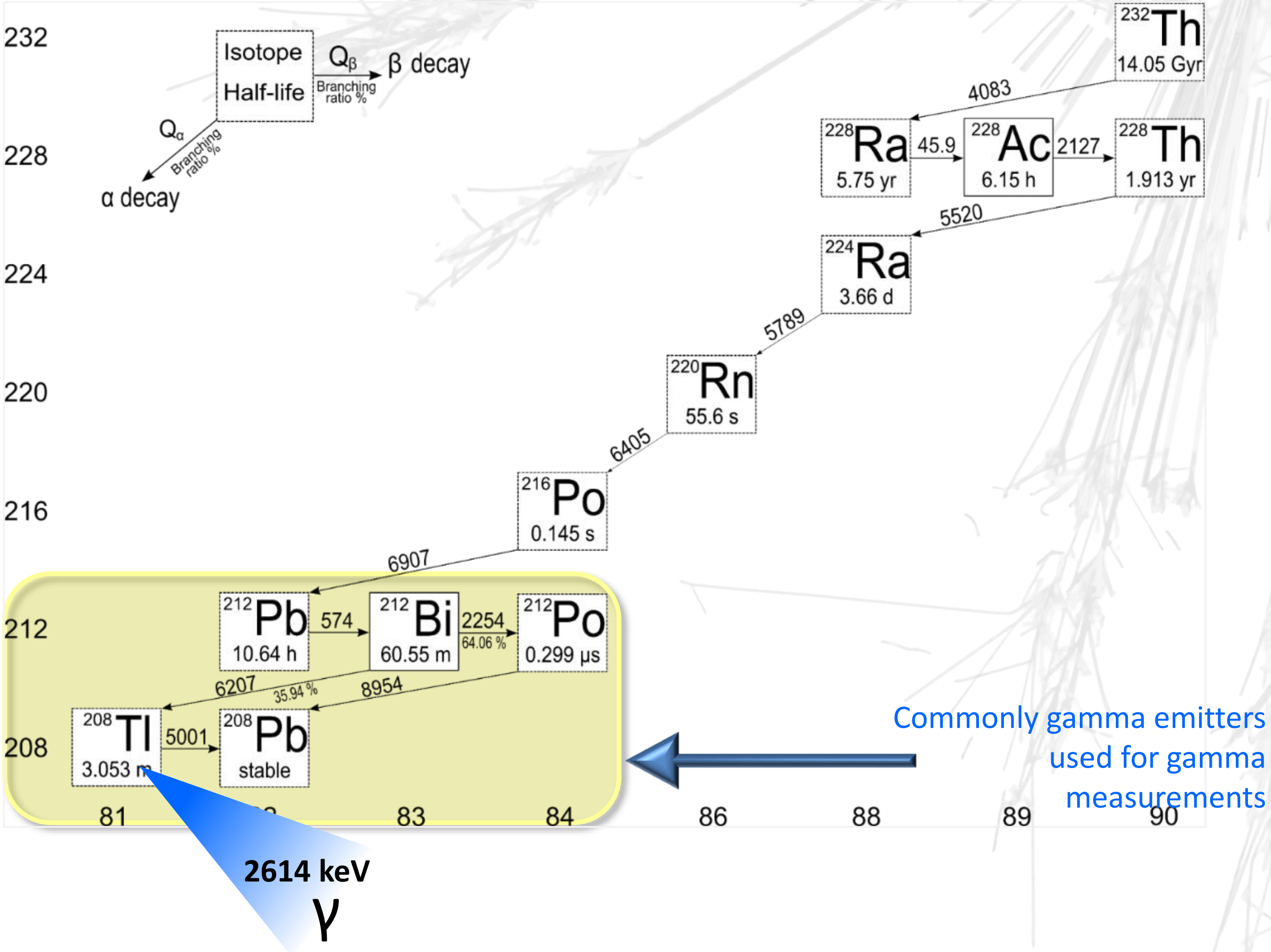
Thorium 232

^{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 timed larger than uranium. It can be extracted from monazite sands or as a sub-product of rare Earth elements extraction

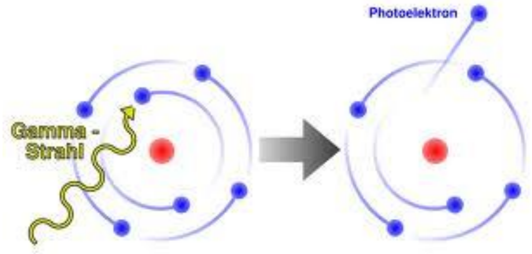




Gamma interaction with matter

Photoelectric effect

[γ + atom→ion + e^-]

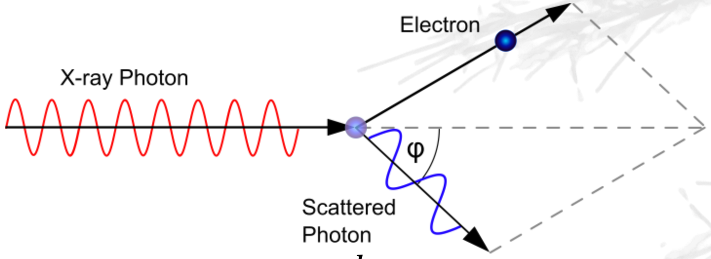


$$E_e = h\nu - E_b$$

- 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'^-]

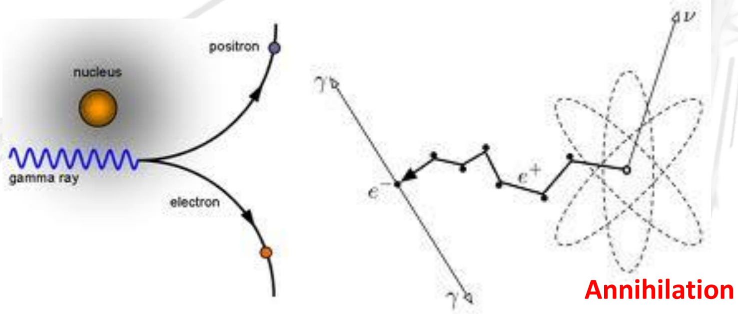


$$E'_\nu = \frac{h\nu}{1 + \frac{h\nu}{m_0 c^2}(1 - cos\theta)}$$

- 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]



- 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

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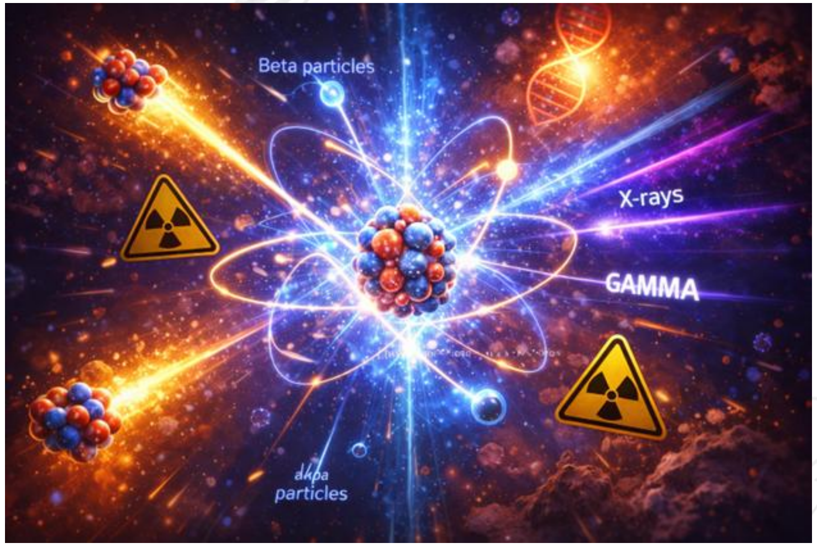
Safety procedure for the use of radioactive source

During the hands on session you will be asked to use radioactive laboratory sources to perform measurements



Here the CAEN safety procedure to follow and information regarding a safe use of the items!

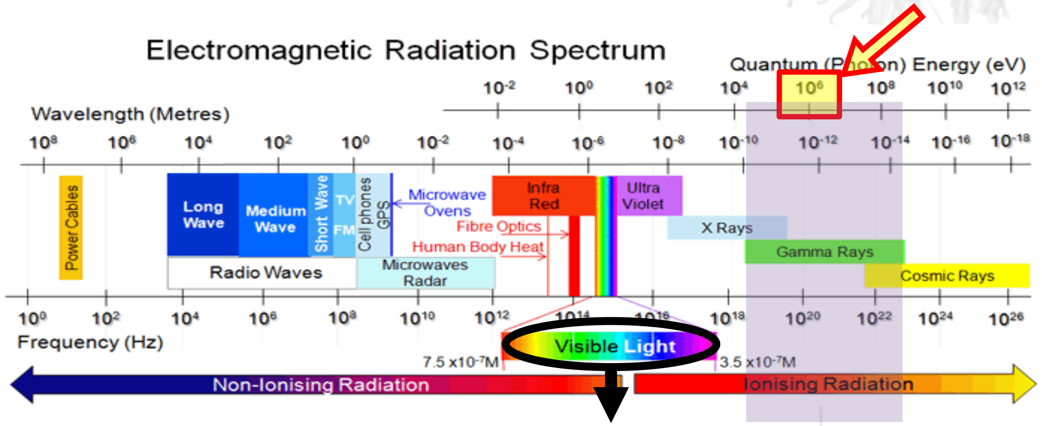
Ionizing radiations

- **Ionizing radiation** is radiation that has enough energy to ionize atoms (or molecules) with which it comes into contact.
- The ability of radiation to ionize an atom, or to penetrate more or less deeply into matter, depends not only on its energy but also on the type of radiation and the material with which the interaction occurs.
- Ionizing radiation is divided into two main categories:
  - those that produce ions **directly** (charged particles such as α, β^-, and β^+ particles)
  - those that produce ions **indirectly** (neutrons, gamma rays, and X-rays).

Exposure to ionizing radiation can originate from:

- **External Irradiation** – the radiation source is located outside the body;
- **Internal Irradiation** – the radiation source is inside the body, introduced through ingestion or inhalation.

The Italian Exposure limits for the general population and for workers are regulated by the Legislative Decree DLGS.101/2020.



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

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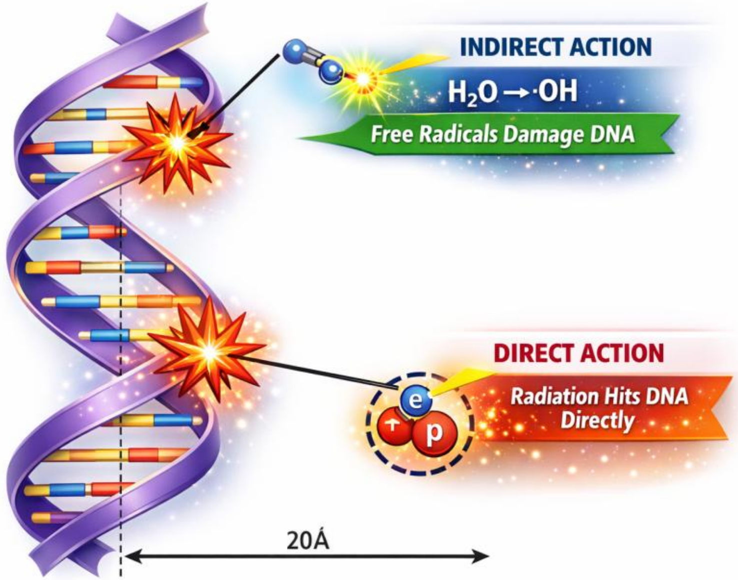
Radiation Damages

“Everything is poison, and nothing is without poison; only the dose makes the poison.”
— *Paracelsus* (Einsiedeln, 14 novembre 1493 – Salisburgo, 24 settembre 1541)

Even water can become lethal — if the dose is high enough!

Radiation is not “good” or “bad” by itself!
What matters is how much energy is deposited in matter — especially in living tissue.

Ionizing radiation causes two main damegs:



Direct Damage

Radiation directly ionizes DNA → molecular structure is altered.

Indirect Damage

Radiation ionizes water (≈70% of the human body)
→ produces free radicals (e.g., OH•)
→ radicals attack DNA and other biomolecules.

Most biological damage is actually indirect!

The dose

- **Absorbed Dose (D)** in a medium: average energy absorbed per unit mass of the irradiated medium
  - **unit of measurement**: Gray (Gy, mGy, µGy)

Louis Harold Gray
(Londra, 10 November 1905 – 9 July 1965)

- **Equivalent Dose (H_t)** in tissue T: average absorbed dose in tissue T, weighted by the type of radiation R
  - **unit of measurement**: Sievert (Sv, mSv, µSv)

$$H_T = w_R D$$

where $\mathbf{w_R}$ is the radiation weighting factor

Radiation Type	w_R
β ; γ ; X	1
α	20

- **Effective Dose (E)**: takes into account the relative radiosensitivity of different tissues/organs
  - **unit of measurement**: Sievert (Sv, mSv, µSv)

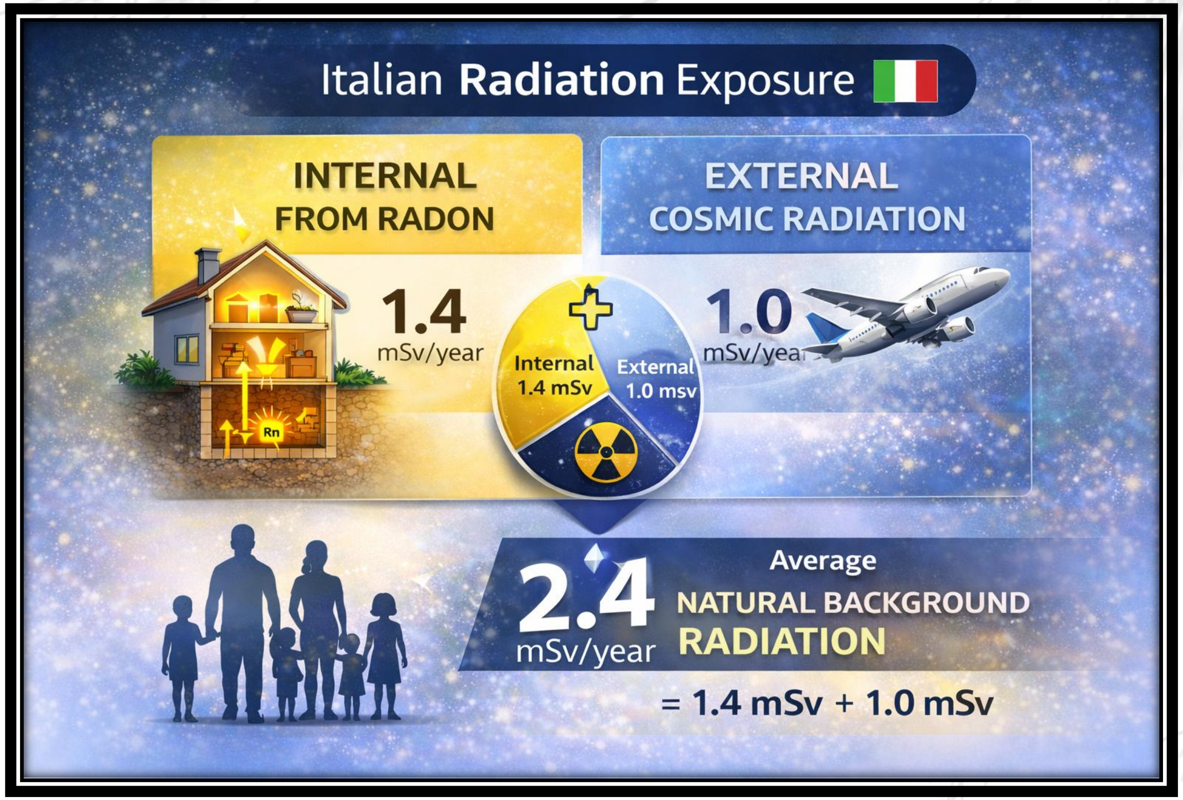
$$E = \sum_T w_T H_T$$

$\mathbf{w_T}$ = tissue weighting factor

Organs	w_T
Gonads	0.20
Bone marrow, colon, stomach, lung	0.12
Bladder, breast, liver, esophagus, thyroid, other organs	0.05
Skin, bone surfaces	0.01

EXPOSURE FROM NATURAL BACKGROUND RADIATION

- Humans have always been exposed to natural ionizing radiation: **natural background radiation**
- The natural background radiation consists of **terrestrial radiation** (produced by primordial or cosmogenic radionuclides undergoing radioactive decay) and **cosmic radiation** (of extraterrestrial origin).
- A key component of terrestrial radiation is **Radon (Rn-222)**. It is a naturally occurring radioactive gas, odorless, tasteless, invisible, and 7.5 times heavier than air. It spreads everywhere, and its concentration varies from place to place.



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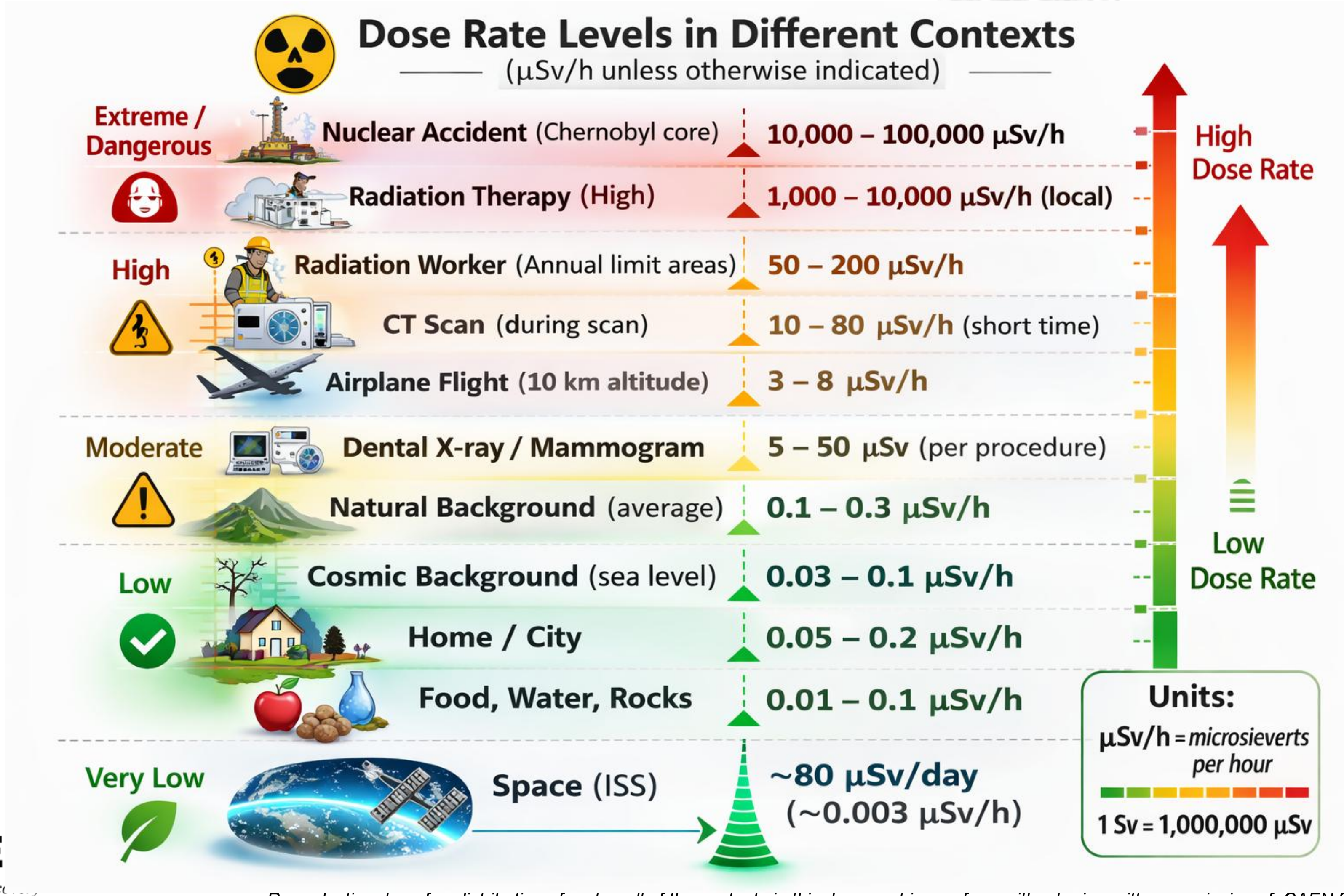
From not natural background!



- **1 mSv/year** effective dose
- **15 mSv/year** equivalent dose to the lens of the eye
- **50 mSv/year** equivalent dose to the skin and extremities

Justification

Any practice involving radiation must be justified in advance.

Optimization

Each practice must be carried out so as to keep exposure ***as low as reasonably achievable*** (**ALARA**), taking economic and social factors into account!

Compliance with dose limits

All exposures must remain within the established dose limits.

PROTECTIVE MEASURES

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Strict adherence to operational procedures established by the **Internal Radiation Protection Regulations** in force

PROCEDURES FOR THE USE OF CALIBRATION RADIOACTIVE SOURCES

- Sealed sources
- Must be handled with **disposable gloves**– never touch the sources with bare hands
- The operator must always keep the radioactive source at the **maximum possible distance** from themselves and from any other person who may be present in the experimental area.
- The **time of use** of radioactive sources must always be kept to the **strict minimum necessary**.
- Radioactive sources must always be **clearly marked** at the point of use, with a **yellow trefoil warning sign** indicating the **type and activity** of the source.
- One of the operators must wear the active dosimeter to monitor the dose

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GammaEDU - SP5640

Portable detection backpack for environmental radioactivity!

- NaI(Tl) (0.3 liter) Scintillator Crystal coupled to a PMT
- Power Supply included
- Identification of Natural Radiation [^{238}U, ^{232}Th, ^{40}K]
- Autonomy up to 6-8 hours
- Tablet included with GammaEDU Application
- Bluetooth and Wi-Fi Connectivity
- Geolocation and ability to view the map on Google Earth

Suitable also for High School Students!

RADIOLAB

INFN Istituto Nazionale di Fisica Nucleare

GammaEDU - App

Measurement Results

Geolocation
Picture
^{40}K, ^{214}Bi, ^{208}Tl Isotopes CPS
^{40}K, ^{238}U, ^{232}Th Abundances

Data

Displayed on Google Earth
.kmz file
Easy to share

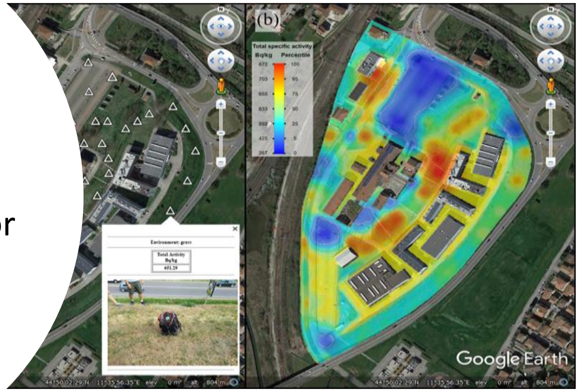
Interface

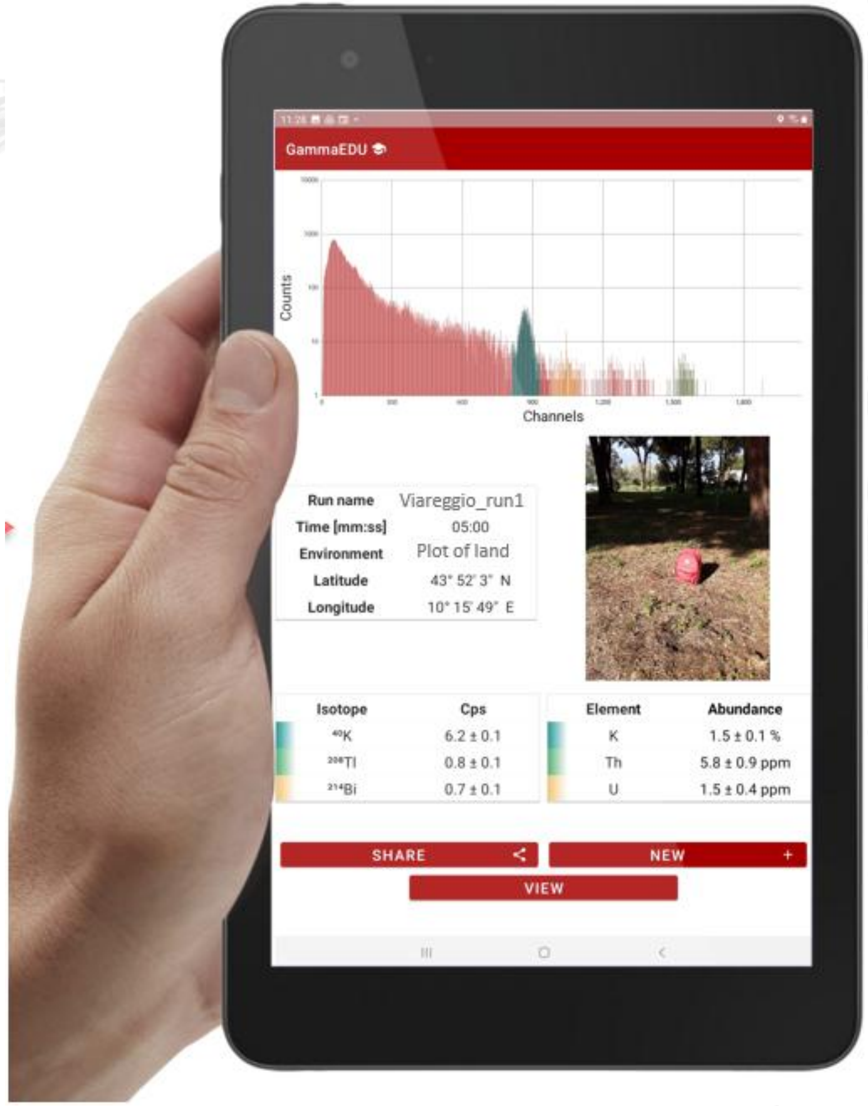
Bluetooth connection

Maps development

Studies in the field of earth sciences

New software for creating maps with color intensity associated with local radioactive contribution!





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GammaEDU – What's Inside?

Tablet

Tablet 10' with GammaEDU Application

Digital MCA Unit - S2580 - GAMMASTREAM

- 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
- Coupled with NaI(Tl) with a 14-pin PMT
- 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

General Properties

Density(g/cm³)	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

NaI(Tl) Scintillator

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

Dimension: 0.3 l

Applications

- Environmental Gamma detection and spectroscopy
- Mapping of potential radon-prone areas
- Environmental monitoring in land field
- Geochemical and mineral exploration
- Statistics
- Customs protection and border control

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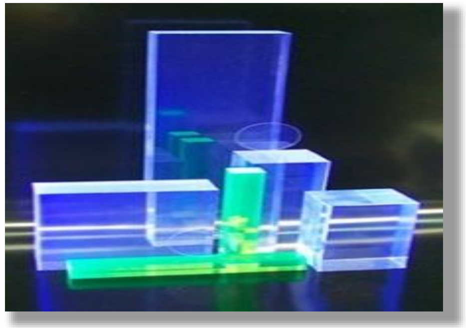
Detection Mechanism

1 Energy deposition by an ionizing particle

- Generation of light
- Transmission of scintillation light
- Detection

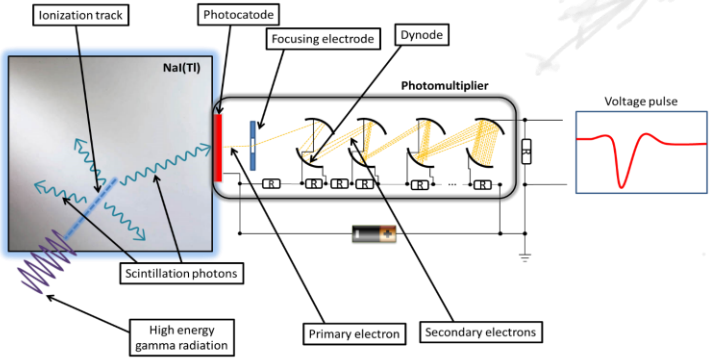
What are scintillators used for?

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



2 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.



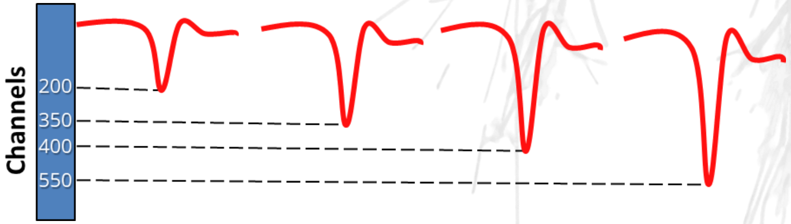
- *PMT collects and transforms the light produced by the scintillator into an electrical signal*
- *The intensity of the output current pulse is proportional to the energy of the incident photon!*

3

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.



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

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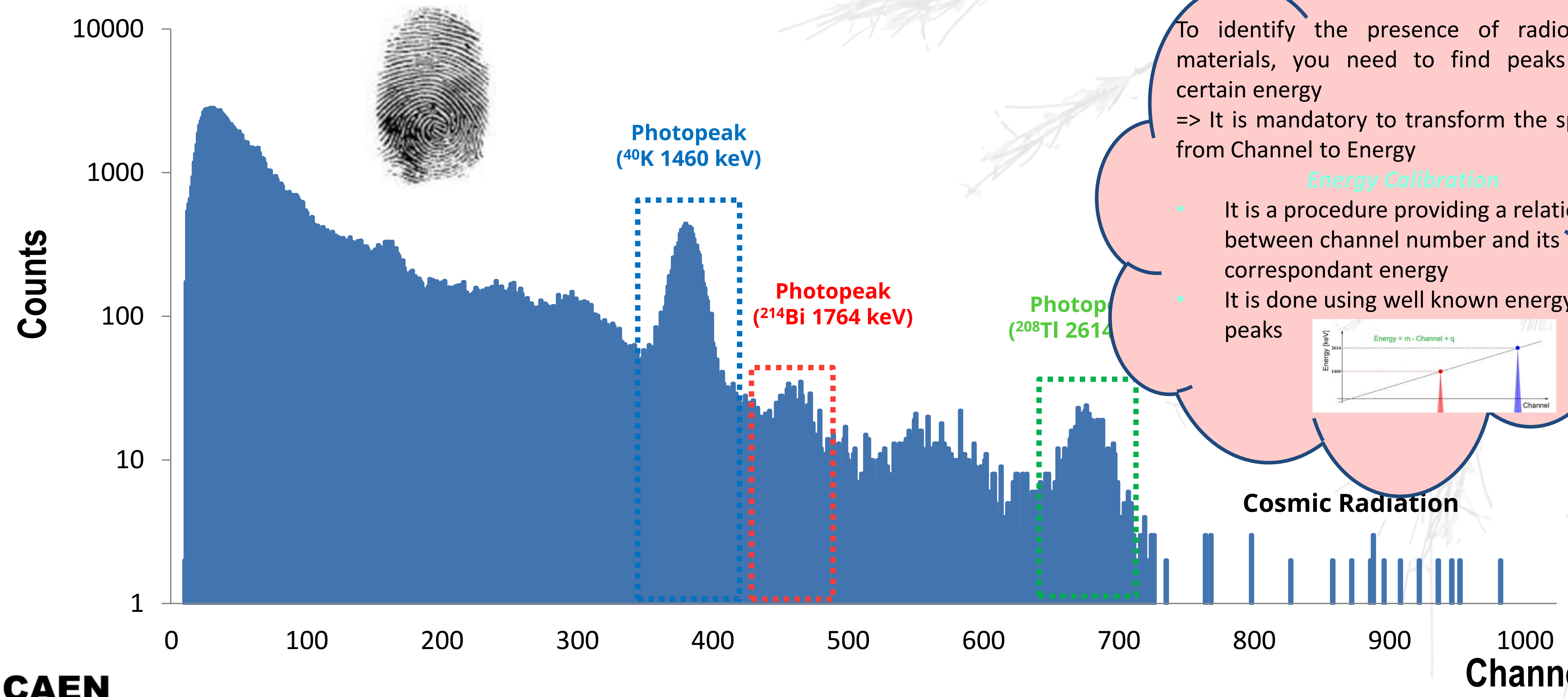
Typical Gamma Spectra

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 inte

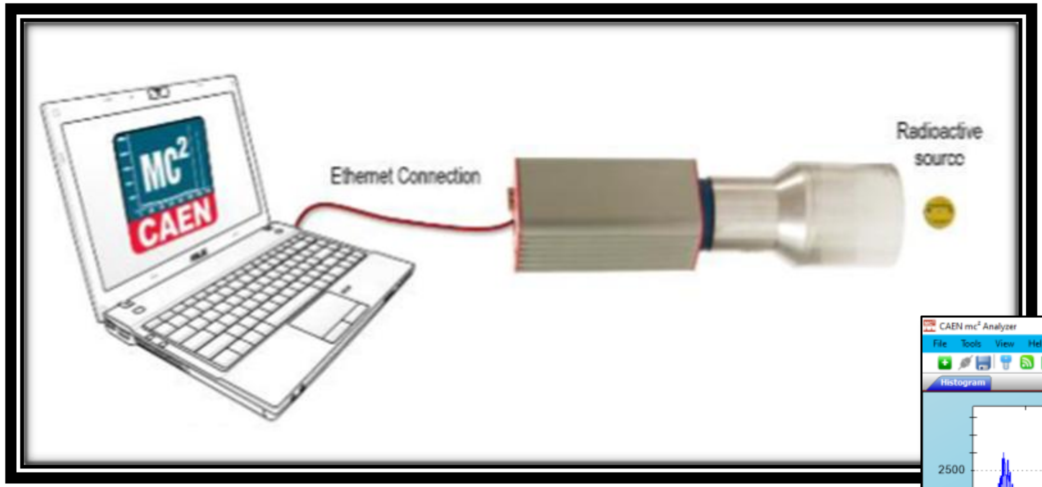


To identify the presence of radioactive materials, you need to find peaks of a certain energy
=> It is mandatory to transform the spectra from Channel to Energy

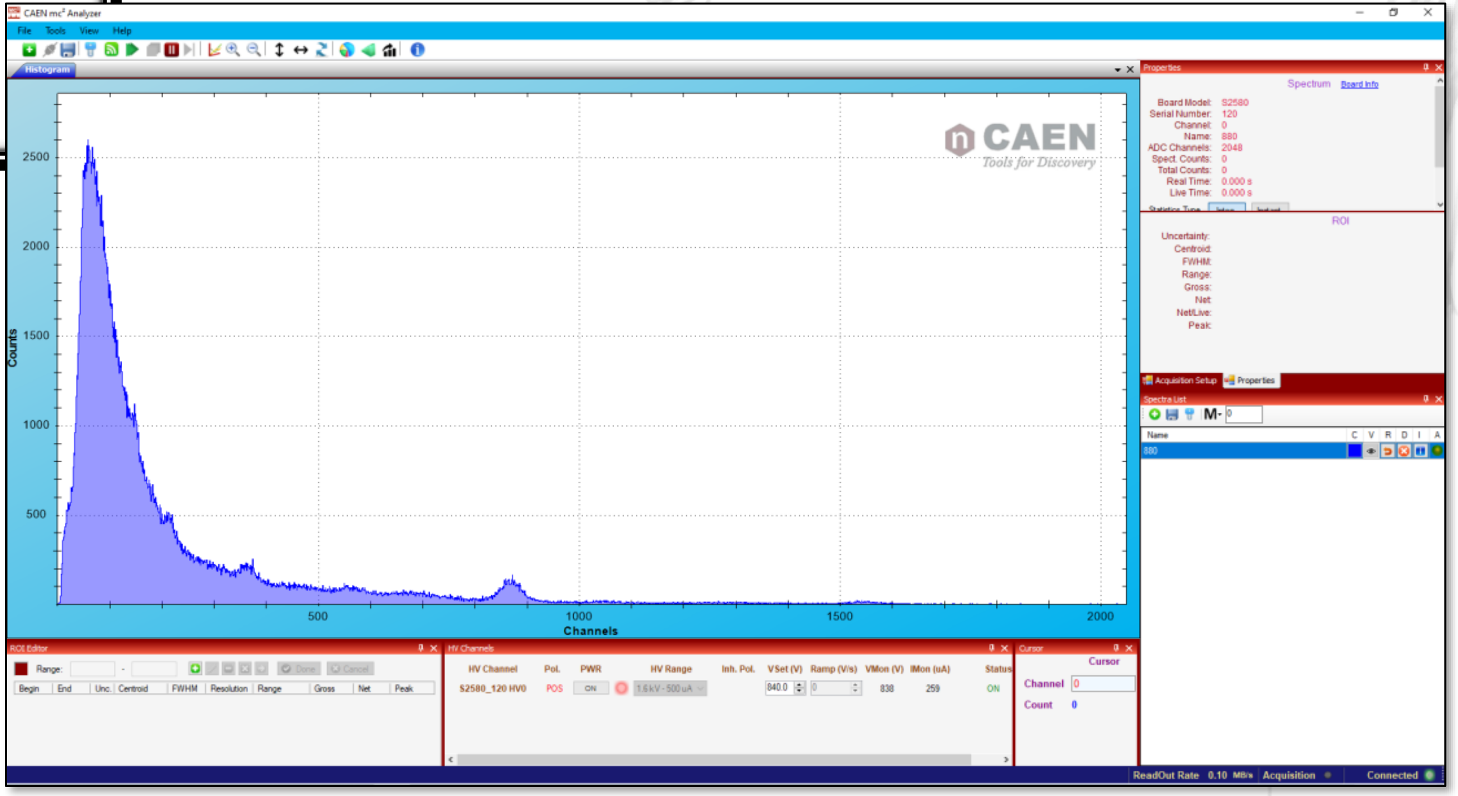
Energy Calibration

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

MC² Software



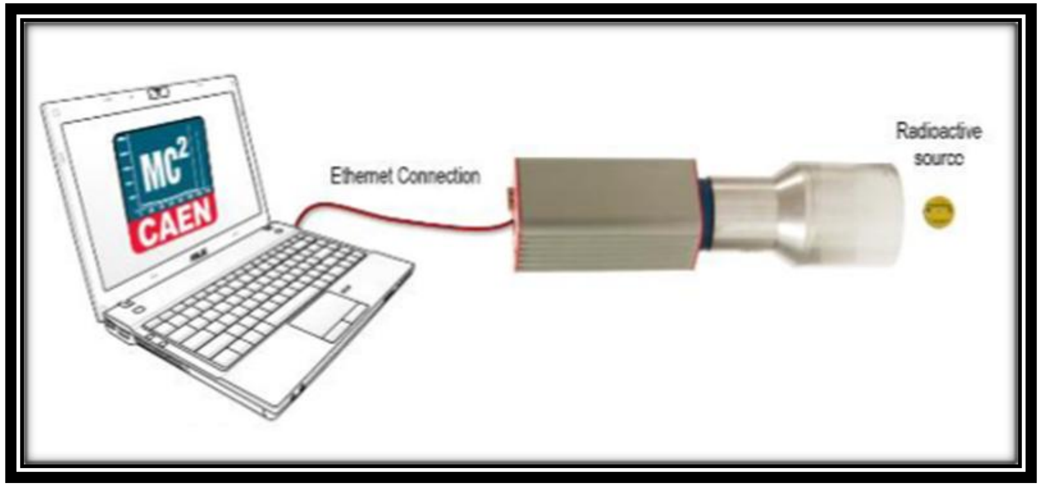
The Multi-Channel Analyzer (**MC² Analyzer**) software has been designed as a user-friendly interface to manage the acquisition with pulse height algorithms



MC²Analyzer software allows the user:

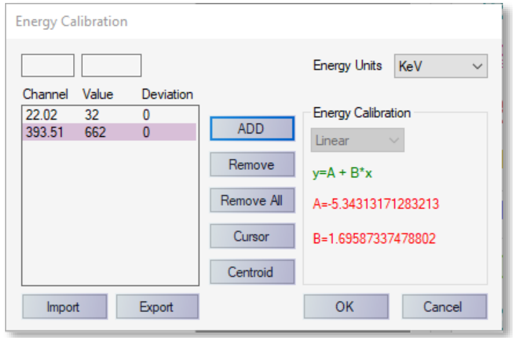
- ❑ to program the relevant DPP-PHA parameters
- ❑ to manage the HV channels configuration
- ❑ to collect the spectra
- ❑ to perform basic mathematical analysis, like energy calibration, peak search, background subtraction, peak fitting, etc.

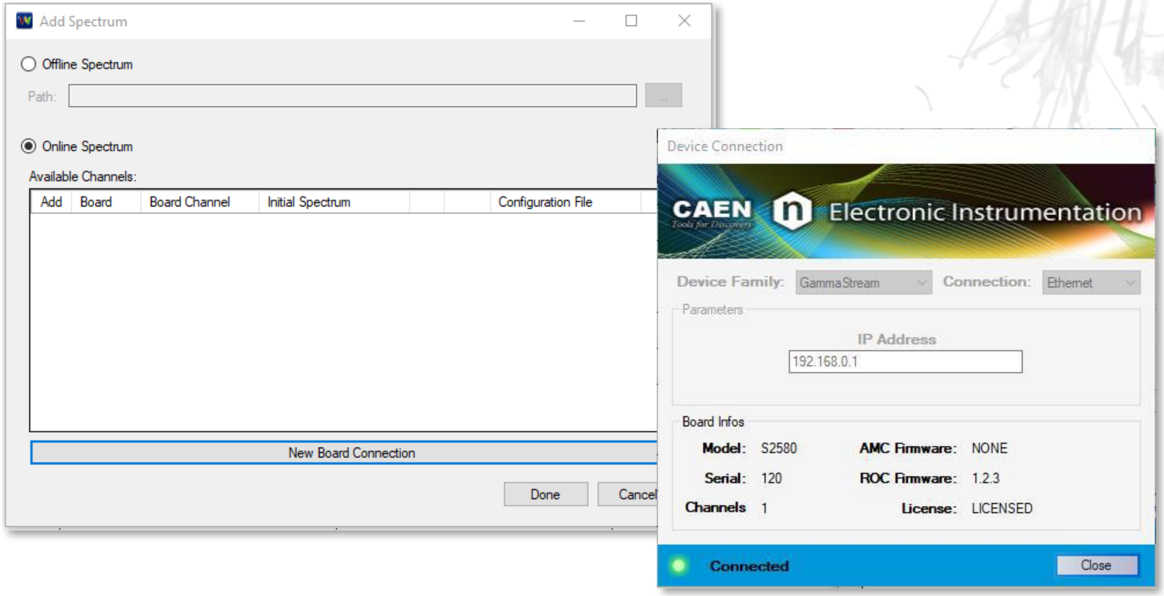
Hands-On Session: Practical instruction



- Connection *γstream* to the MC^{2}Analyzer software through Ethernet connection.
- Launch the MC2Analyzer software and connect it to the *γstream*
- From the main panel of MC^{2}Analyzer software GUI select: "File-> Add Spectrum" or press the button
- Select "Online Spectrum" and "New Board Connection" to connect the software to the device
- Select "Type = Ethernet" on the "Device Connection" window, and write the IP Address of γstream. (192.168.0.1)

- The parameters configuration is already applied but to change or verify it, it is necessary to open the "Signal Inspector" window through the icon
- Then press PLAY to start the acquisition, STOP to stop it.
- From the "Roi Editor" window add a ROI
- To calibrate the spectrum, press the icon





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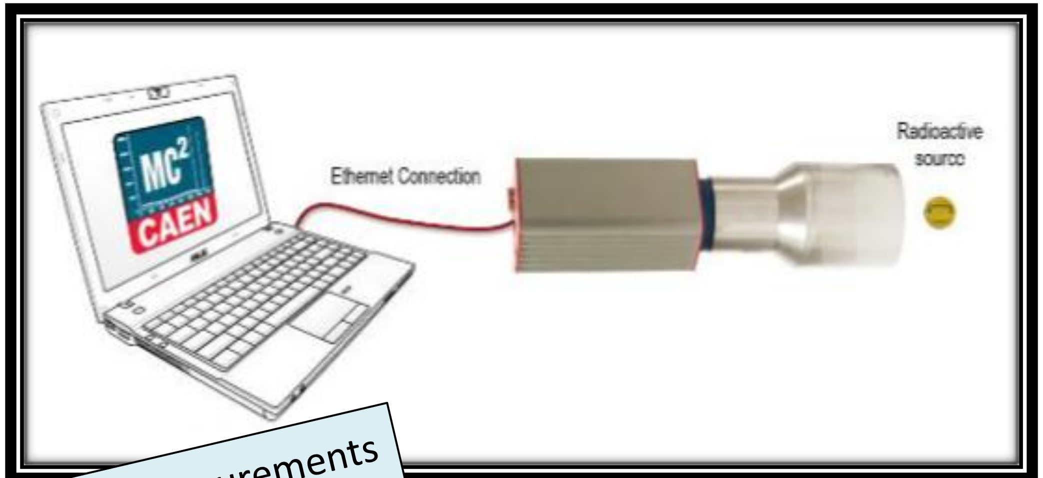


Ensure all measurements will be performed with the sources positioned at 5 cm distance from the detector.

Before to stop the session, verify that all spectra are properly saved!

Gamma Spectroscopy and Source Identification

Radioactive sources:

- Co-60 (known activity)
- Cs-137 (known activity)
- Unknown source (unknown activity and radionuclide)

Spectra Acquisition

- Acquire the Co-60 spectrum with an acquisition time of 3 minutes.
- Acquire the Cs-137 spectrum with an acquisition time of 3 minutes.
- Acquire the combined spectrum (Co-60 + Cs-137).
- Perform energy calibration using the combined spectrum.
- Save the calibrated spectrum in .n42 format.

Unknown Source Identification

- Acquire the spectrum of the unknown source using the same geometry configuration (same distance).
- Apply the previous energy calibration.
- Use LaraWeb and the provided documentation (list of possible radionuclides) to: Identify the most plausible radionuclide.
- Save the spectrum of the unknown source in .n42 format.

CAEN Educational Website

[CAEN EduLab - CAEN EduLab](#)

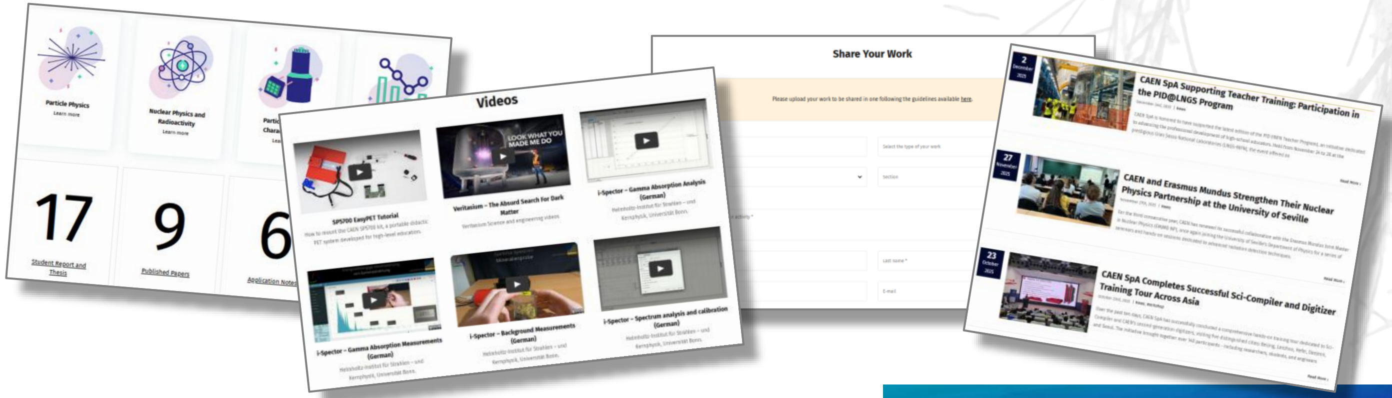
Upload the hands-on report at the end of the day!

Innovative Scientific Network

Caen introduces a global platform for Modern & Nuclear Physics education, enabling seamless sharing of experiments for students and professionals.

Interactive and User-Friendly Resources

The platform also features interactive tools that enhance communication and collaboration among members, along with comprehensive guides tailored specifically to each user’s needs.



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Thank you for your attention!

Cristina Mattone, PhD
+39 348 915 6856
c.mattone@caen.it

Reach us at educational@caen.it
Visit www.edu.caen.it
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Spare Slides

Energy Calibration

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

$^{40}K \Rightarrow E_K = 1460\ keV$
$^{208}Tl \Rightarrow E_{Th} = 2614\ keV$

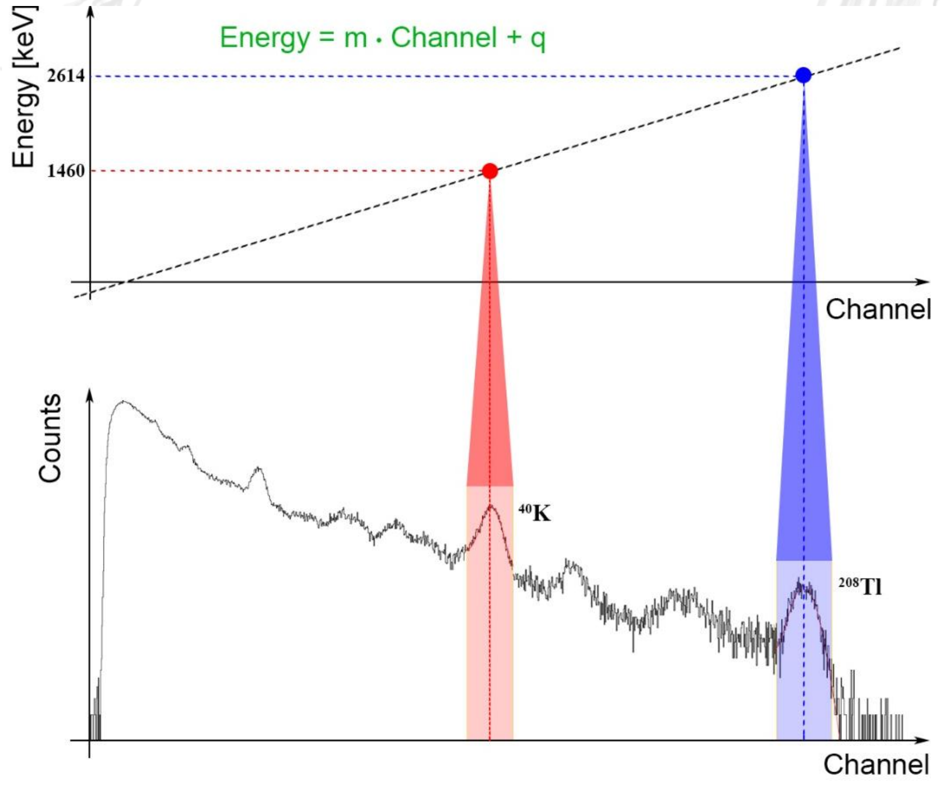
^{208}Tl is coming from the radioactive chain of the ^{232}Th and is the highest energy gamma from natural sources

$A = (E_{Th}, Ch_{Th})$
$B = (E_K, Ch_K)$

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

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

Multichannel Calibration



Oggetti e gioielli radioattivi

https://www.bag.admin.ch/bag/it/home/gesund-leben/umwelt-und-gesundheit/strahlung-radioaktivitaet-schall/radioaktive-materialien-abfaelle/gebrauchs-gegenstaende.html

Guarapari (Brasile)

Le spiagge di Guarapari, nello Stato di Espirito Santo in Brasile, sono simili a quelle di Karunagappalli: contengono monazite. Sono stati misurati livelli massimi di 175 mSv/anno.

Karunagappalli (India)

Nello Stato indiano sudoccidentale del Kerala, Karunagappalli ha una popolazione che supera i 25 mila abitanti. Nella sabbia della spiaggia si trovano granuli di monazite che provengono dai vicini depositi di Terre rare. La monazite è un fosfato che oltre alle Terre rare contiene impurità di uranio e torio.

Arkaroola (Australia)

Le sorgenti di Paralana, ad Arkaroola nello Stato di South Australia (700 km a nord di Adelaide), raccolgono la radioattività rilasciata da rocce ricche in uranio risalenti a oltre 1 miliardo di anni fa

etc etc etc