# Radioactivity mechanism and interaction of radiation with matter

RBPA course **(PHYS-450)**

12.09.2025

**Veljko GRILJ, PhD**
Responsible de recherche
Service de Radiotherapie
and Institut de Radiophysique
CHUV

## INSTITUE FOR RADIATION PHYSICS (IRA)

- affiliated institute of the Department of Radiology at CHUV
- provides expertise in:

**Medical physics** – physics of radiation therapy and medical imaging

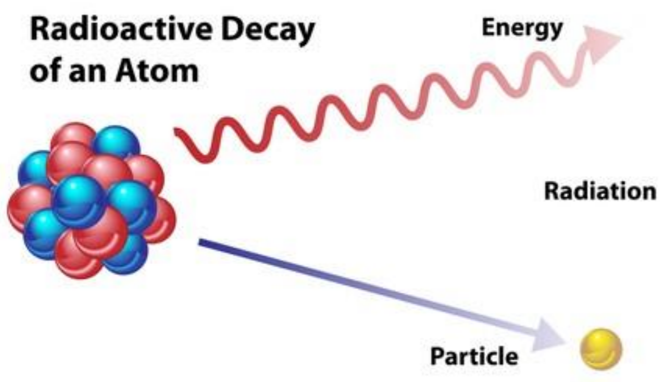
**Radiation protection** – protection of personnel working with ionizing radiation

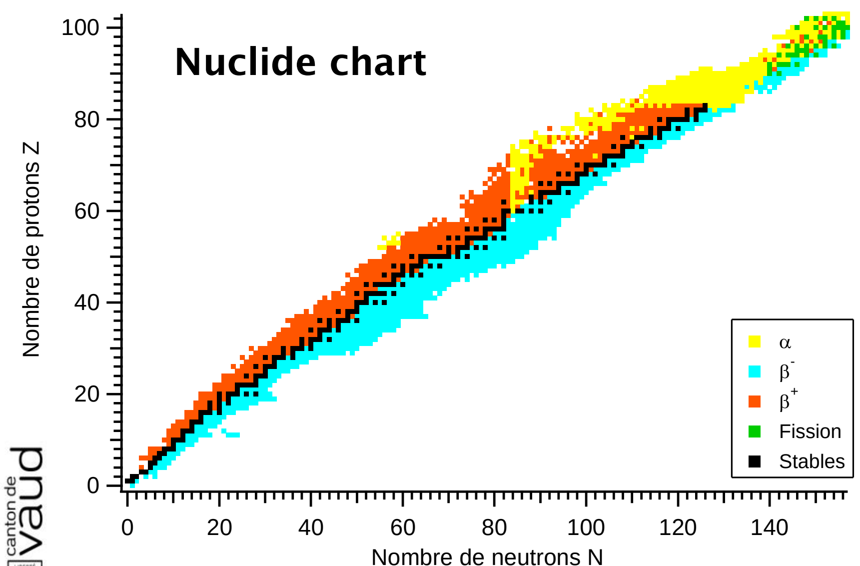
**Radio-pharmaceutical chemistry** – support for nuclear medicine

**Radiometrology** – support to everyone

# Overview of Lecture 1

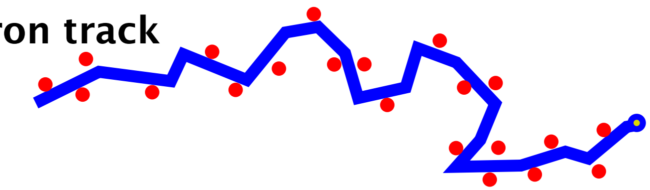
## Radioactivity



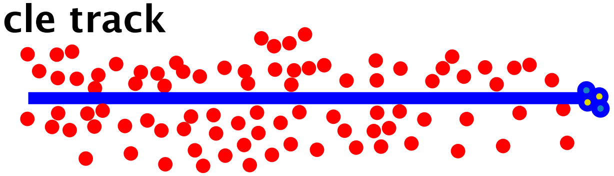




## Interaction of radiation with matter

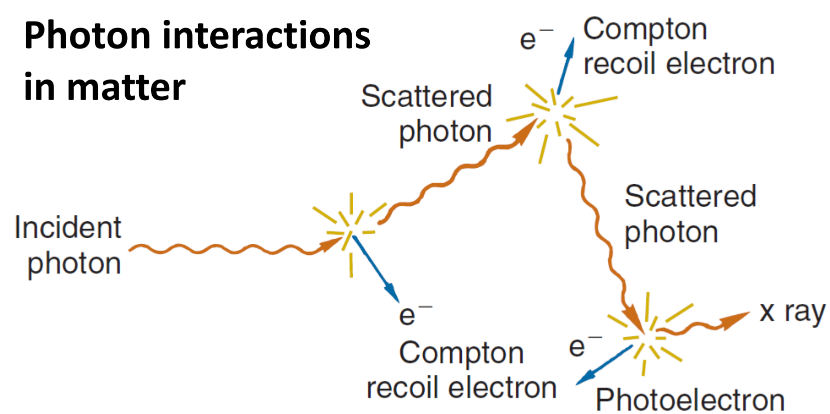
**Electron track**



**α particle track**



**Photon interactions in matter**



- What is radiation?
- Is all radiation dangerous for health?

# Radiation

- Radiation is the transmission of **energy** through space or medium

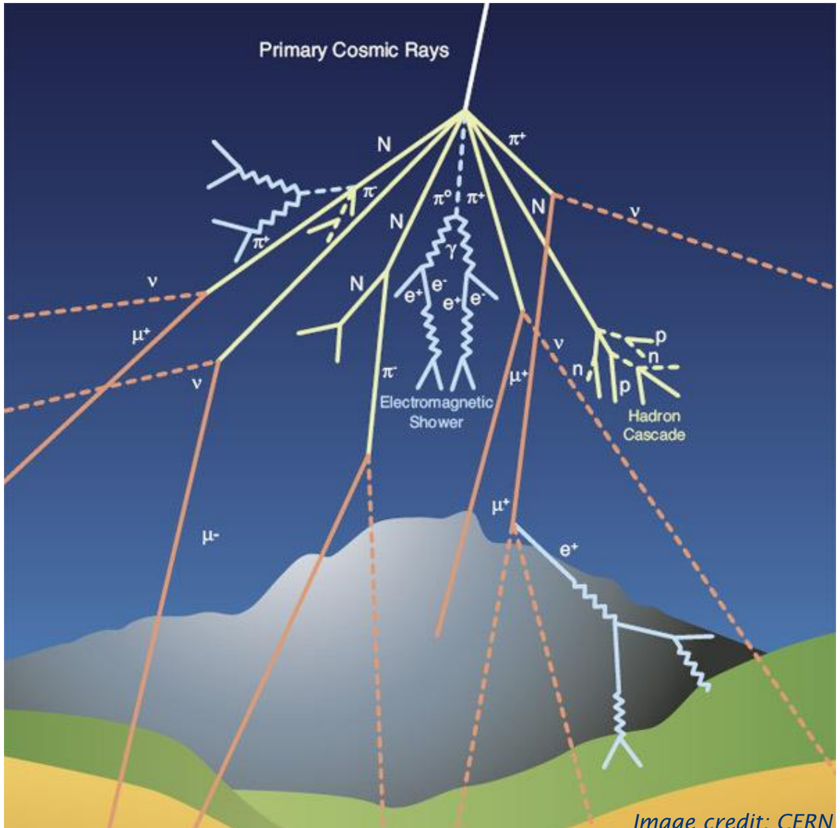
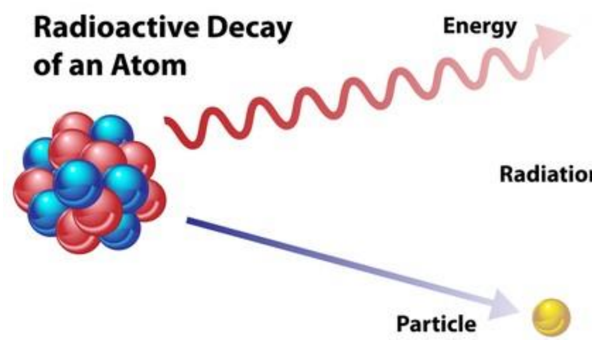


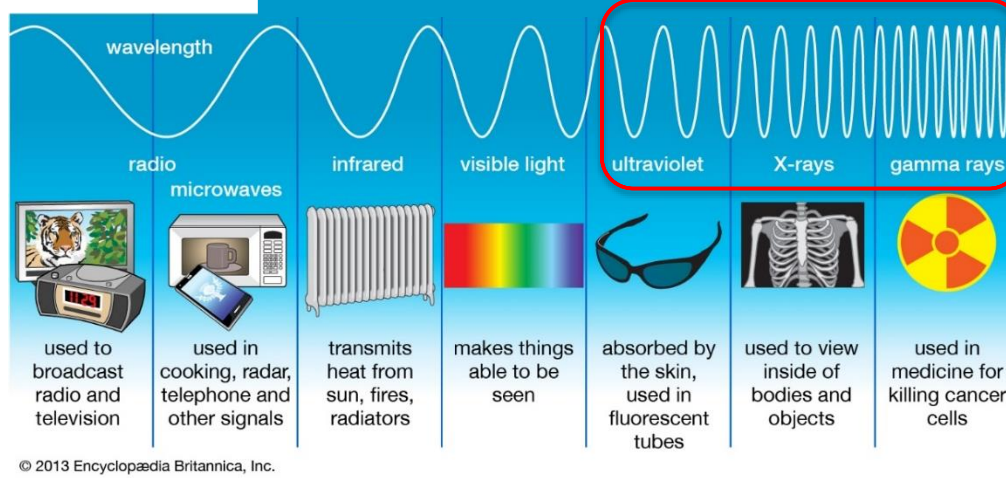

*Image credit: CERN*

Cosmic rays - Particles



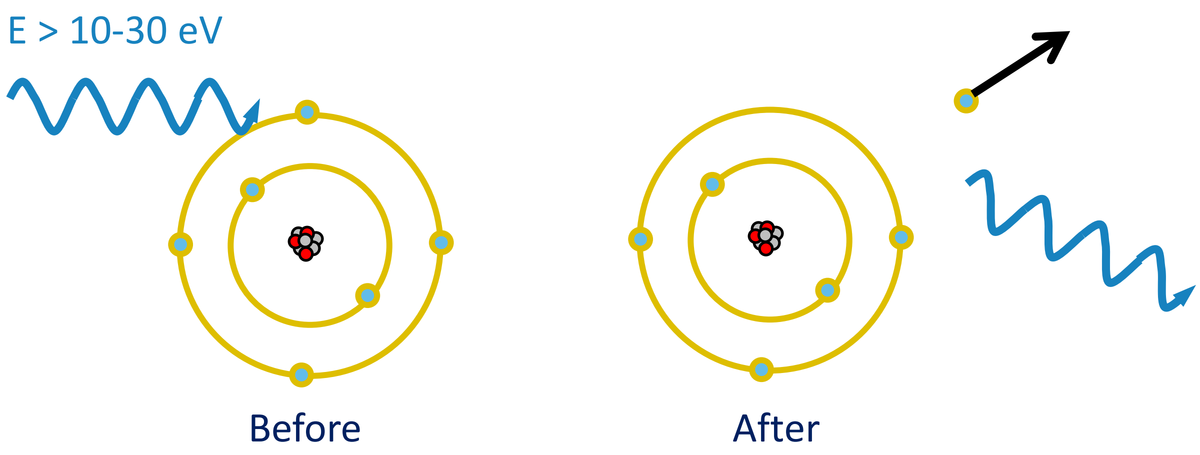

We will be interested only in ionizing radiation since it presents a health hazard

Electromagnetic radiation - Photons



# What is ionizing radiation?

- Ionizing radiation refers to radiation having sufficient energy to remove electrons from atoms or molecules in the medium, including the cells of our bodies

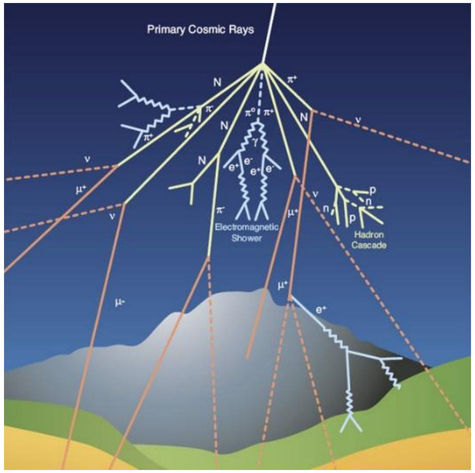



Forms of ionizing radiation:

- Particles (proton, electron, $\alpha$-particles, neutron…)
- Photons (UV, X-rays, $\gamma$-rays)

# Sources of ionizing radiation on Earth

## 1) Cosmic rays

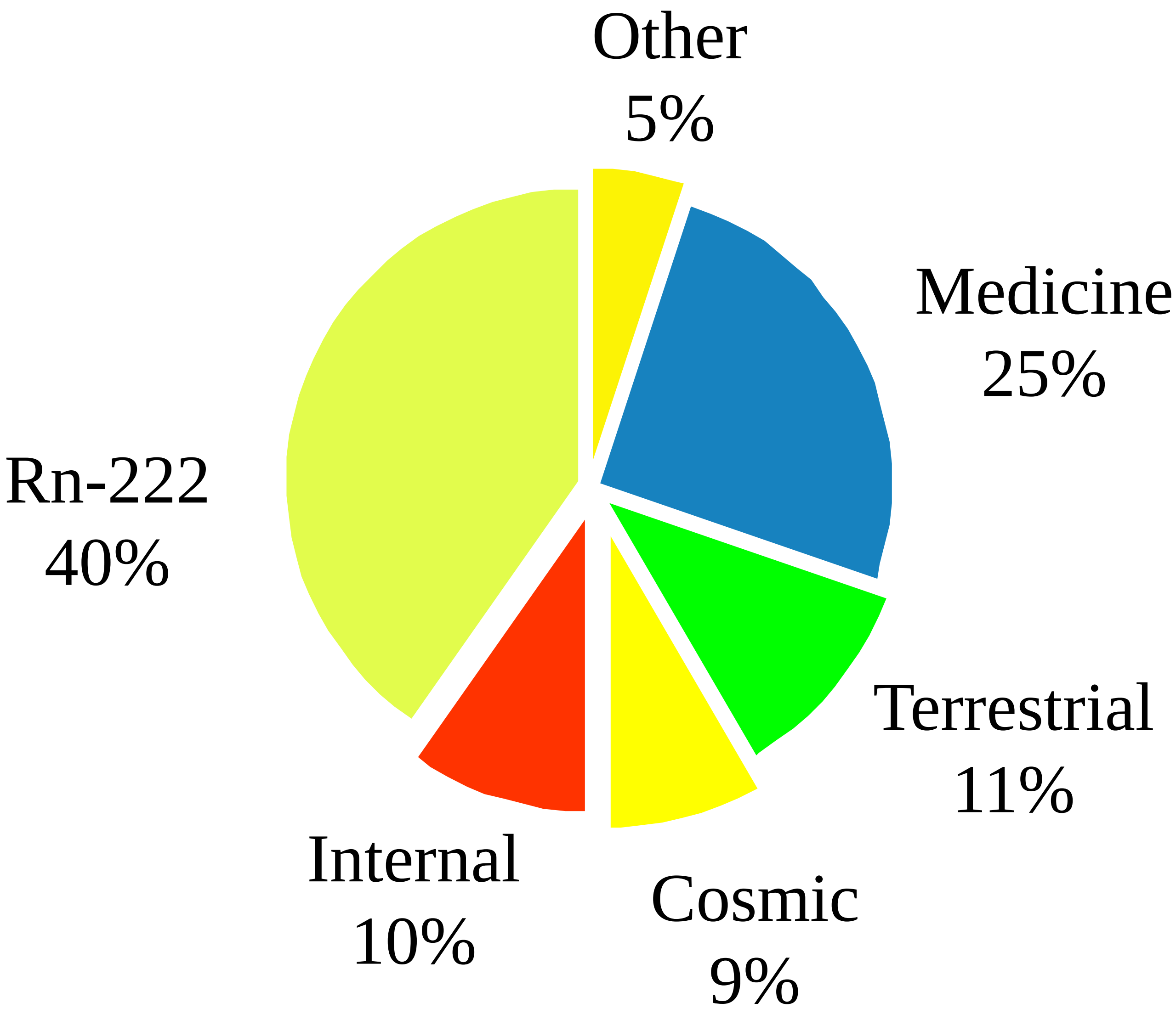



## 2) Naturally occurring radioactive materials

- Food (K-40)
- Ground (U-238, Th-232)
- Air (Rn-222, C-14)

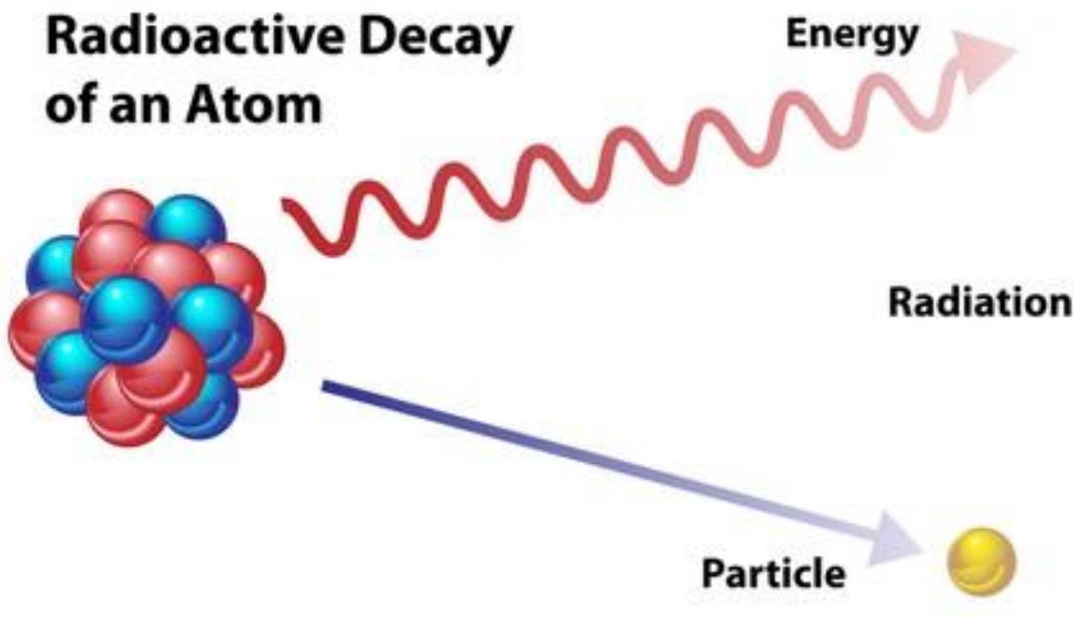

## 3) Man-made

# Population radiation exposure in Switzerland



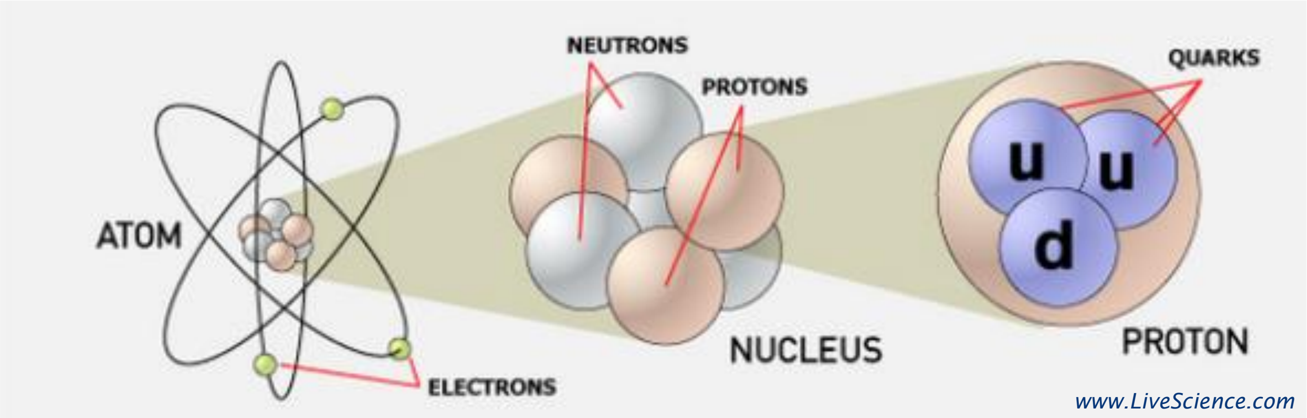
# What is radioactivity?

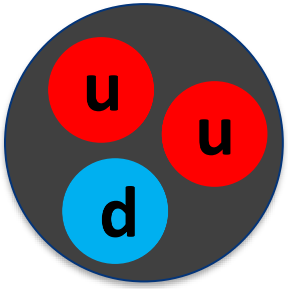
- Spontaneous emission of radiation by an unstable nucleus



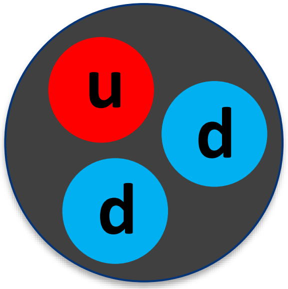

To understand the radioactivity we need to start from the nucleus…

# Zooming into the atom




Quark model of a proton




Quark model of a neutron

Masses:

$m_e$= 511 keV/$c^2$

$m_p$= 938.2 MeV/$c^2$

$m_n$= 939.3 MeV/$c^2$

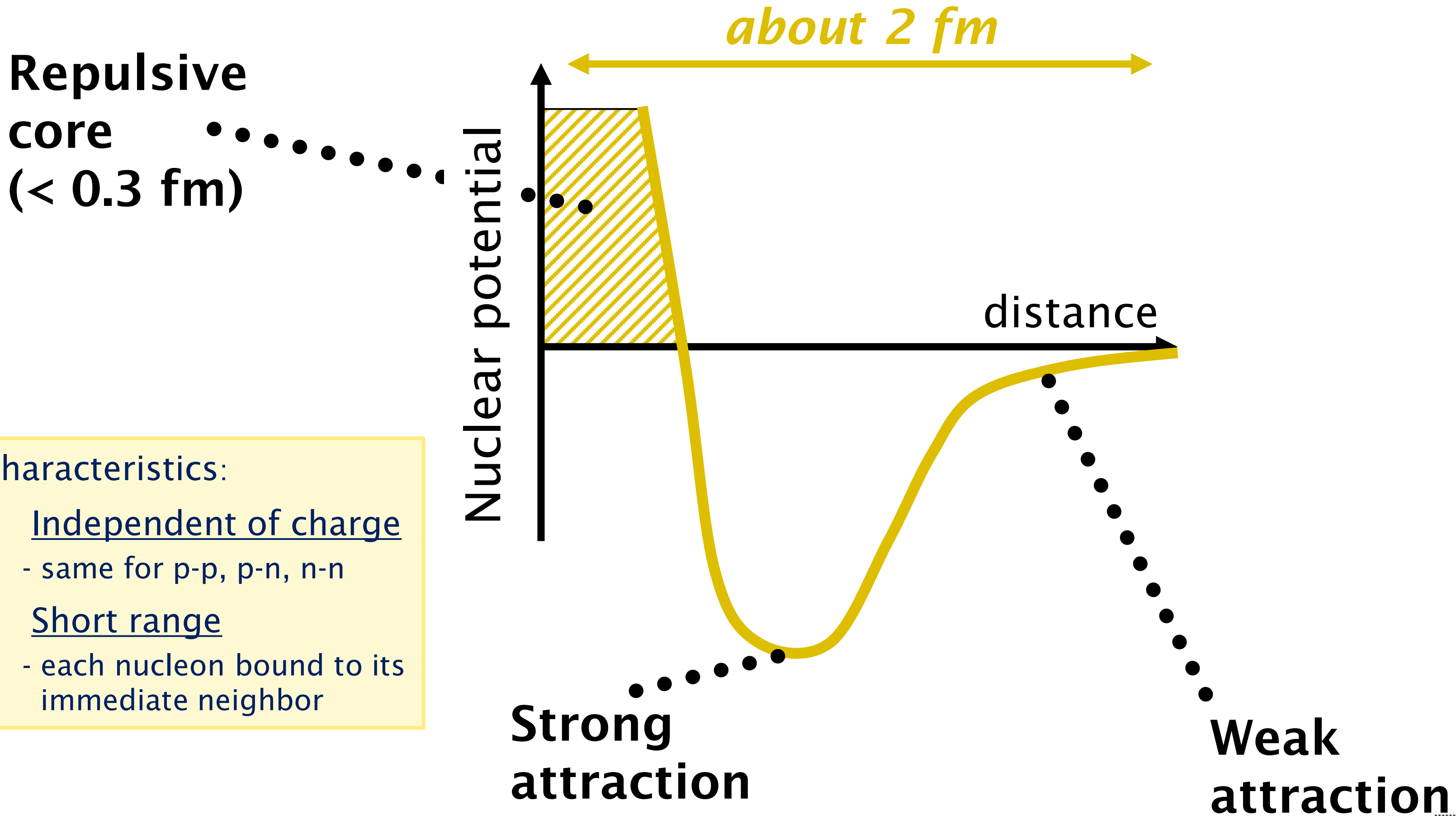
$m_p \approx m_n$

$m_p$ = **1836** $m_e$

# What binds nucleons together?

➢ Protons are positively charged, neutrons have no charge, why the nucleus doesn't fall apart?

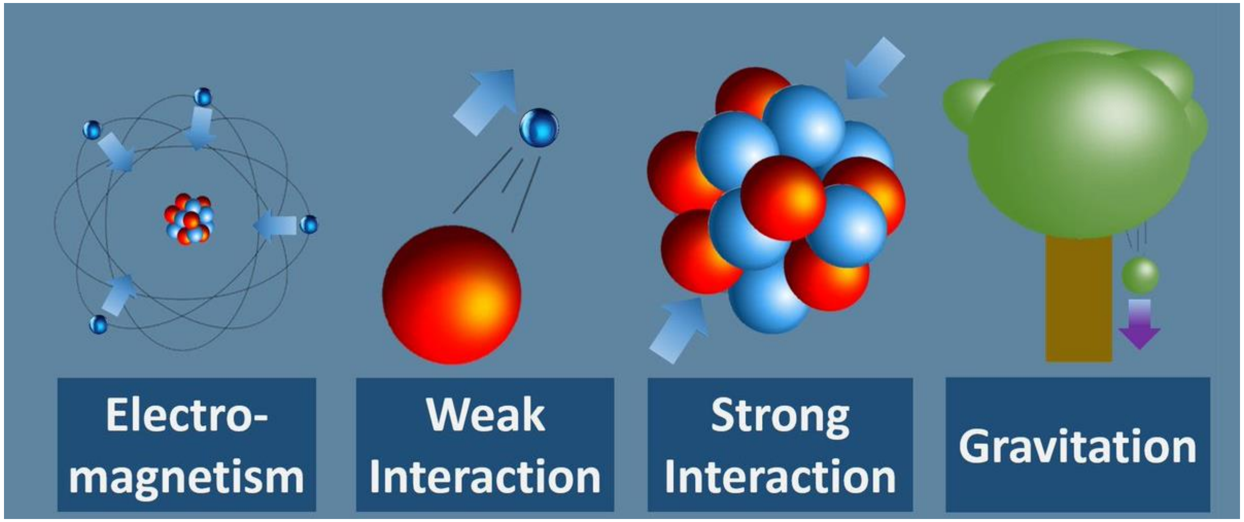
Answer: **Strong nuclear force**




Characteristics:

- Independent of charge
  - same for p-p, p-n, n-n
- Short range
  - each nucleon bound to its immediate neighbor

# Reminder: The four fundamental forces




| force | Relative strength | Range of force | Force carrier |
|---|---|---|---|
| Strong (nuclear) | 1 | ~ $10^{-15}$m | gluon |
| electromagnetic | $10^{-2}$ | ~ $1/r^2$ | photon |
| weak | $10^{-13}$ | < $10^{-18}$m | W boson<br>W boson<br>Z boson |
| gravitational | $10^{-38}$ | ~ $1/r^2$ | graviton |

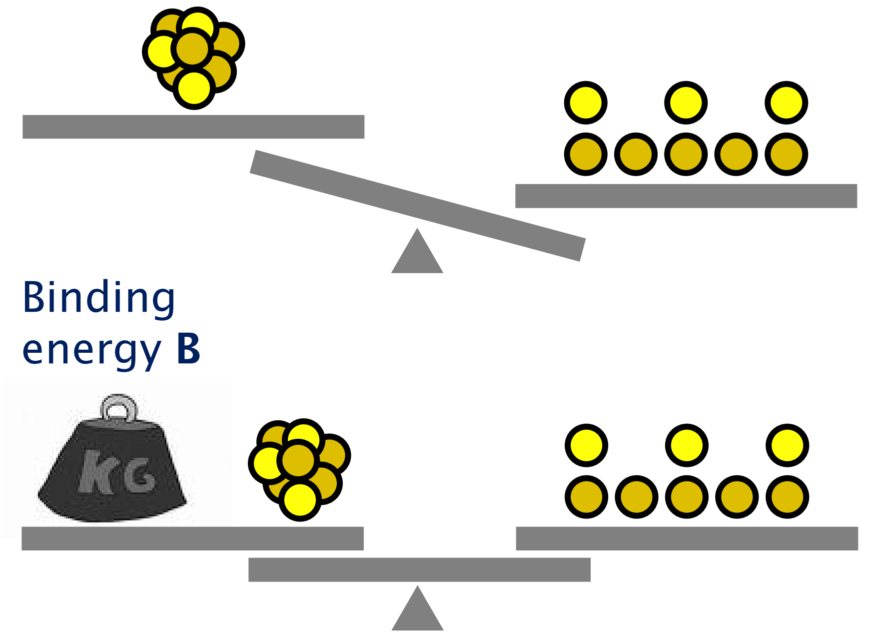
canton de vaud



CHUV

# What binds nucleons together?

➢ The concept of the binding energy (have in mind m ≡ E):



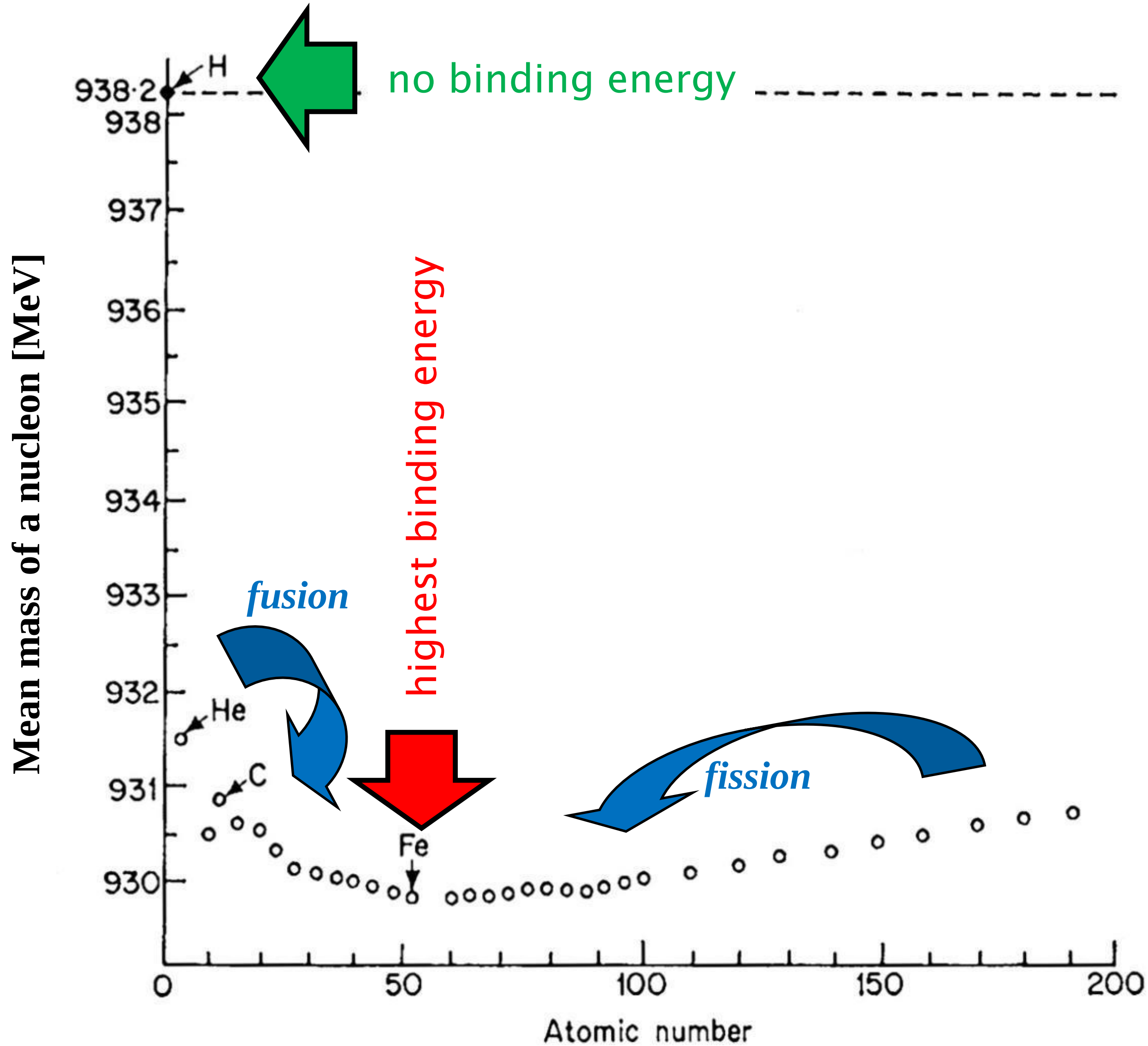

$$B = Z \times m_p c^2 + N \times m_n c^2 - m_A c^2$$

Proton energy

Neutron energy

Nucleus energy

# Binding energy



# Nomenclature

**Element**
- characterised by Z

**Mass number**
- determines the mass of a nucleus : N + Z

$$^{A}_{Z}\mathrm{E}_{N}$$

**Atomic number**
- number of protons or electrons
- chemical characteristics of the element

**Number of neutrons**
- different N for a given Z = isotopes

# Nomenclature

$^{A}_{Z}E_{N}$

- Examples of isotops (same element, different A)

$$^{12}_{6}C_{6} \equiv {}^{12}C \equiv C-12$$
$$^{13}_{6}C_{7} \equiv {}^{13}C \equiv C-13$$
$$^{14}_{6}C_{8} \equiv {}^{14}C \equiv C-14$$

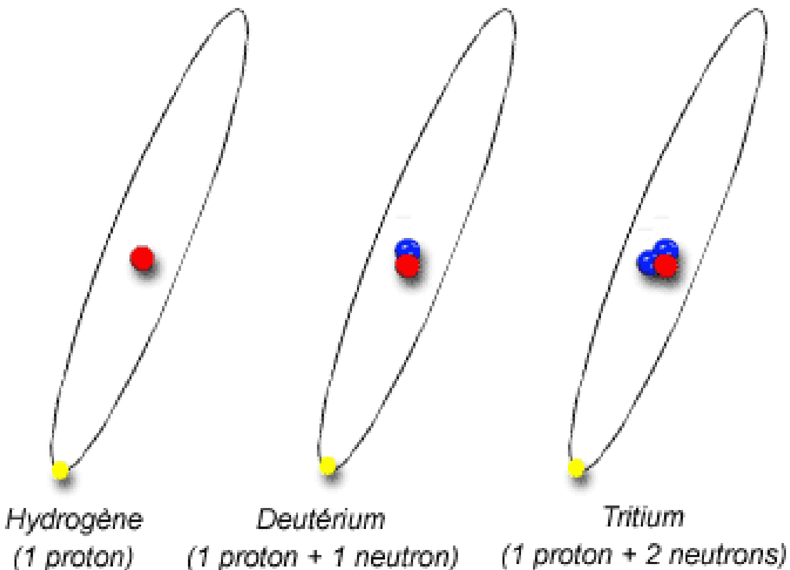
**isotopes of carbon**

# Stable and unstable nuclei

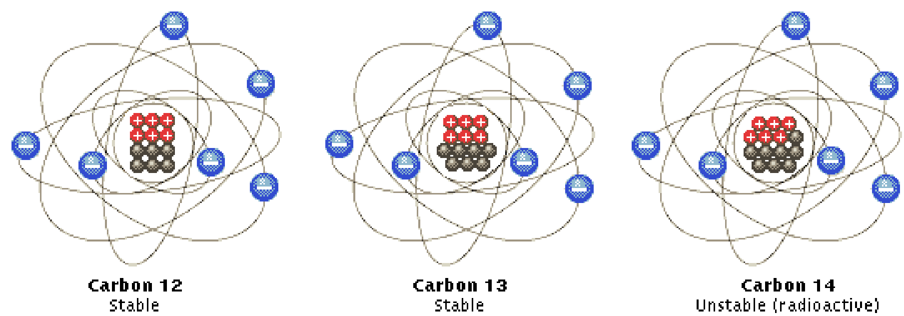
- Stability of a nucleus is determined by the number of protons and neutrons

Hydrogen has three isotopes :
- **hydrogen**: 1 p
- **deuterium**: 1 p, 1 n
- **tritium**: 1 p, 2 n

Carbon has also three isotopes:
- **C-12**: 6 p, 6 n
- **C-13**: 6 p, 7 n
- **C-14**: 6 p, 8 n



radioactive



radioactive

- When an isotope has many more neutrons than protons, or the opposite, its nucleus becomes **unstable**.
- Unstable nucleus **decays** by emitting radiation to release its energy and regain its balance. This phenomenon is called **radioactivity**.

# Radioactive decay

- **Spontaneous** and **stochastic (random)** mechanism
- Decay probability λ [$s^{-1}$]
  - Specific for the considered nucleus
  - Does not change with time

$$dN(t) = -\lambda N(t)dt$$

Solution: Exponential decay

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

# Half life $T_{1/2}$

- The time at the end of which a radioactive atom will have a 50% chance of having decayed. In other words, after $T_{1/2}$ 50% of atoms will decay.
- Does not depend on the initial quantity, but only on the considered nuclide.

$$N(t) = N_0 e^{-\lambda t} \Rightarrow \frac{1}{2} N_0 = N_0 e^{-\lambda T_{1/2}} \Rightarrow T_{1/2} = \frac{ln2}{\lambda}$$

The half-life can vary considerably depending on the elements:

Krypton 89 → ~ 3 minutes

Plutonium 239 → 24 000 years

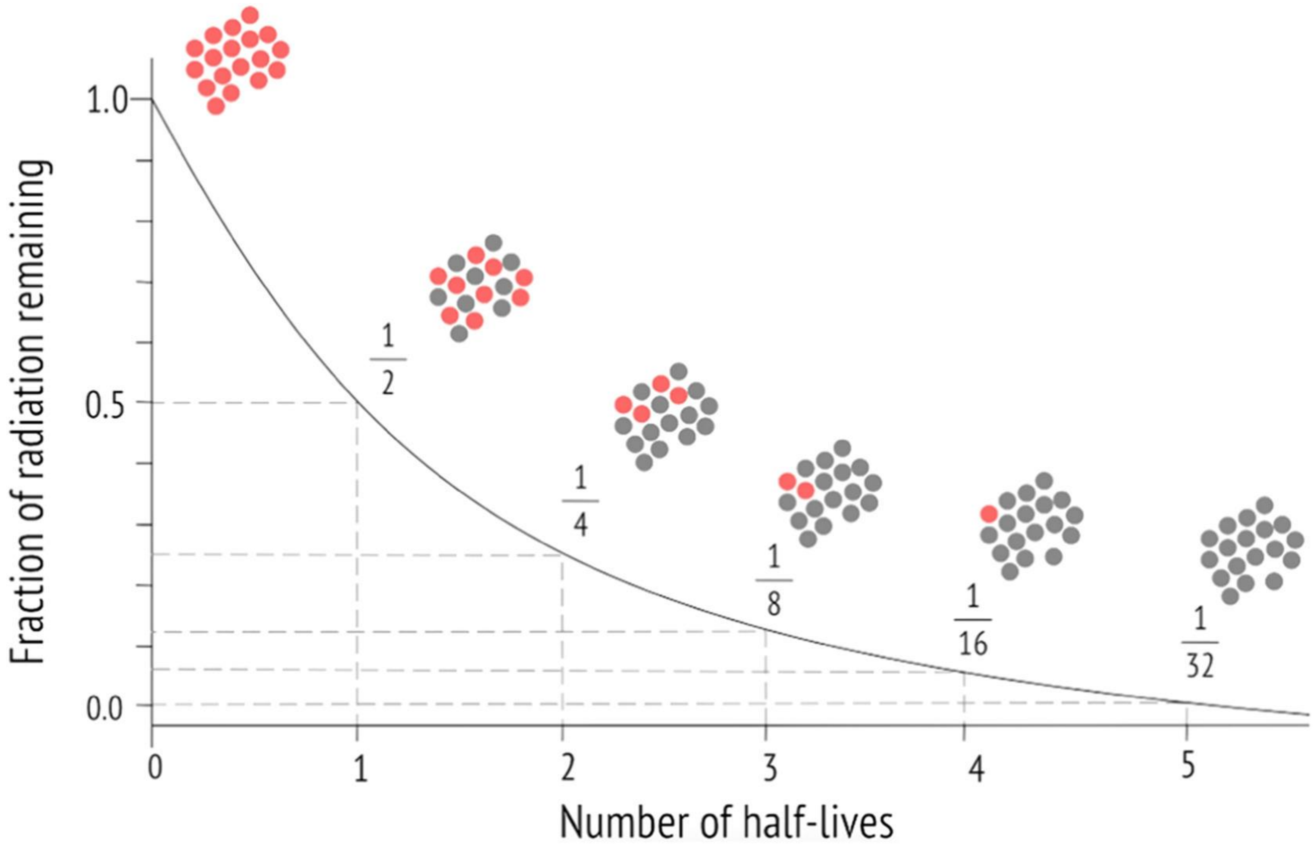
Radon 222 → 3.8 days

Uranium 238 → 4.5 billion years

Uranium 235 → 704 million years

Carbon 14 → 5730 years

# Time dynamic of radioactive decay



# Half life $T_{1/2}$

**Q1:** After how many half-lives the number of parent isotopes will be reduced by approximately a factor of 1000?

# Half life $T_{1/2}$

**Q2:** It took 75 years for 10 g of a radioactive isotope to decay to 1.25 g. What is the half-life of this isotope?

# Half life $T_{1/2}$

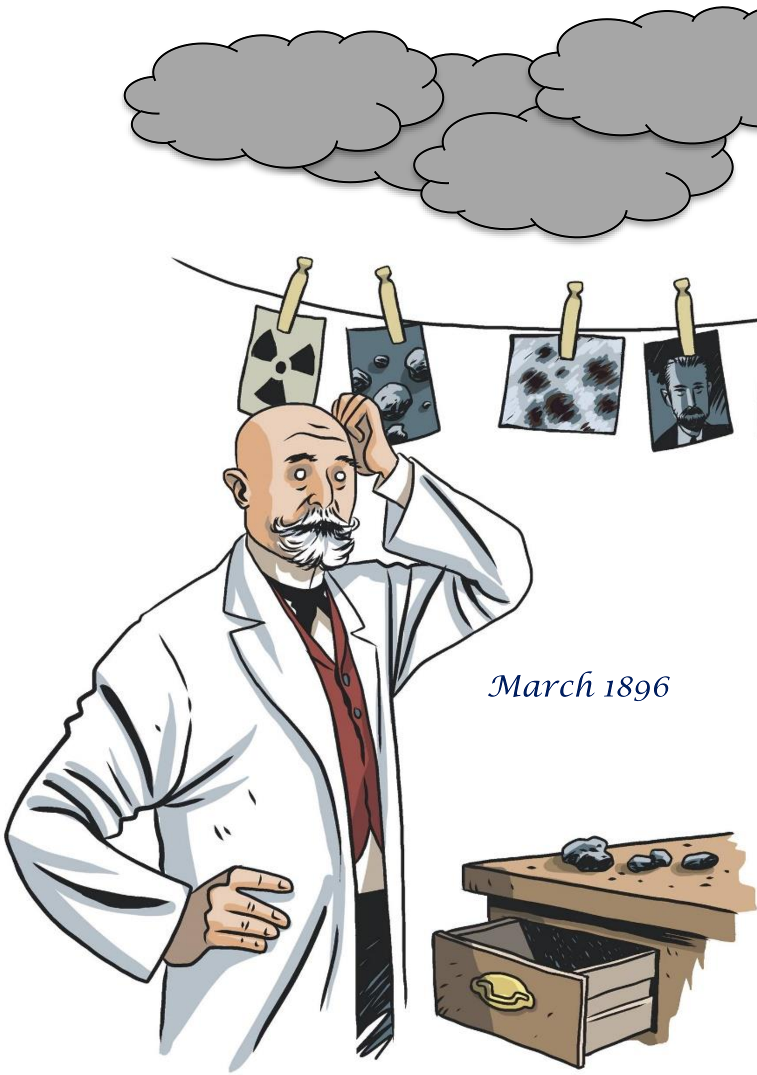
**Q3:** The half-live of americium-241 is 432 y. If 0.0002 g of americium-241 is present in a smoke detector at the date of manufacture, what mass of americium-241 is present after 100.0 y? After 1,000.0 y?

# Activity

- Activity A [Bq]
  - Number of decays per second [**Becquerel** (Bq)]

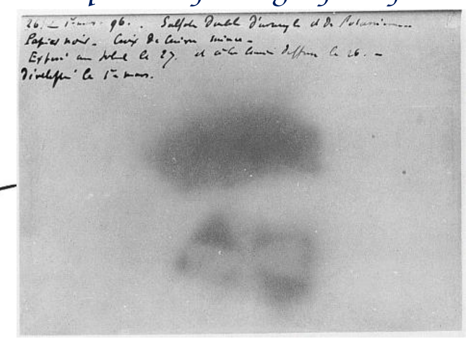
$$A(t) = A_0 e^{-\frac{\ln 2 t}{T}}$$

# Radioactivity: History lesson



March 1896

Becquerel's photographic film



The story in short:

- Few months earlier Roentgen discovered X-rays
- Becquerel believed that phosphorescent uranium salts emit X-rays
- He would wrap photographic plates in black paper, put uranium on top and exposed it to sunlight
- One day weather got bad so he put the plates in the drawer without exposing uranium to sunlight
- However, the plates showed strong exposure

Henry Becquerel

Marie Curie

Pierre Curie

1903 Nobel Prize

canton de vaud

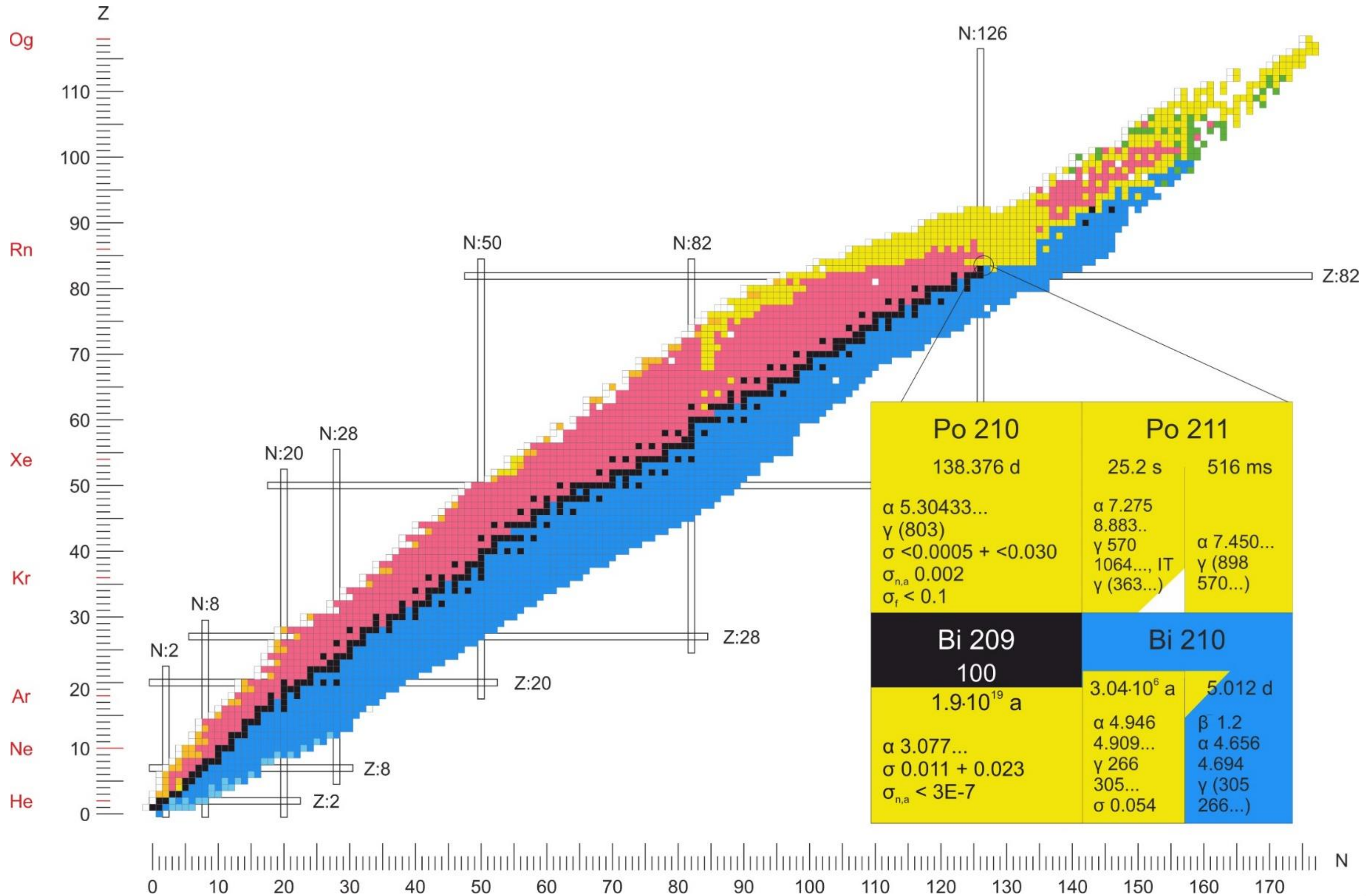
LIBERTÉ ET PATRIE

Image credit: nobelprize.org

CHUV

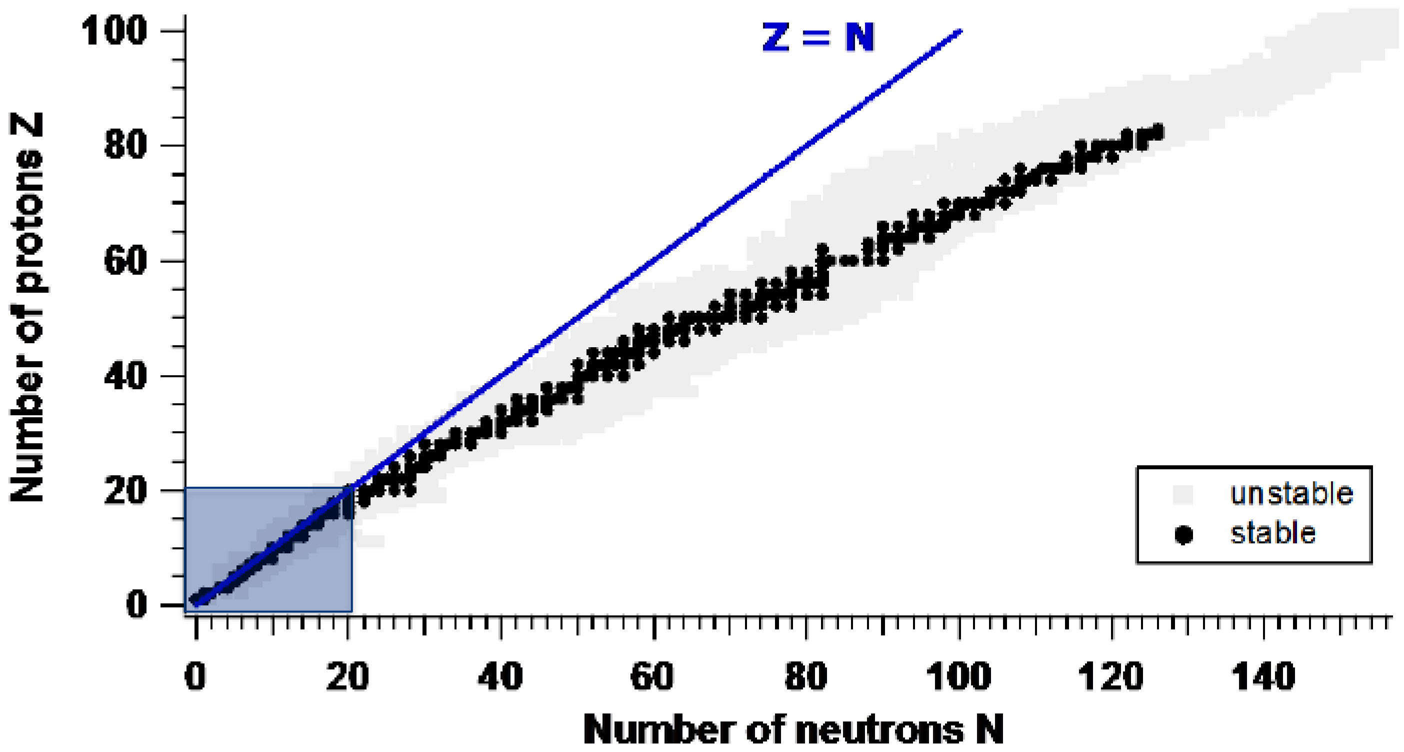
# Where to find look for information?

## Nuclide chart

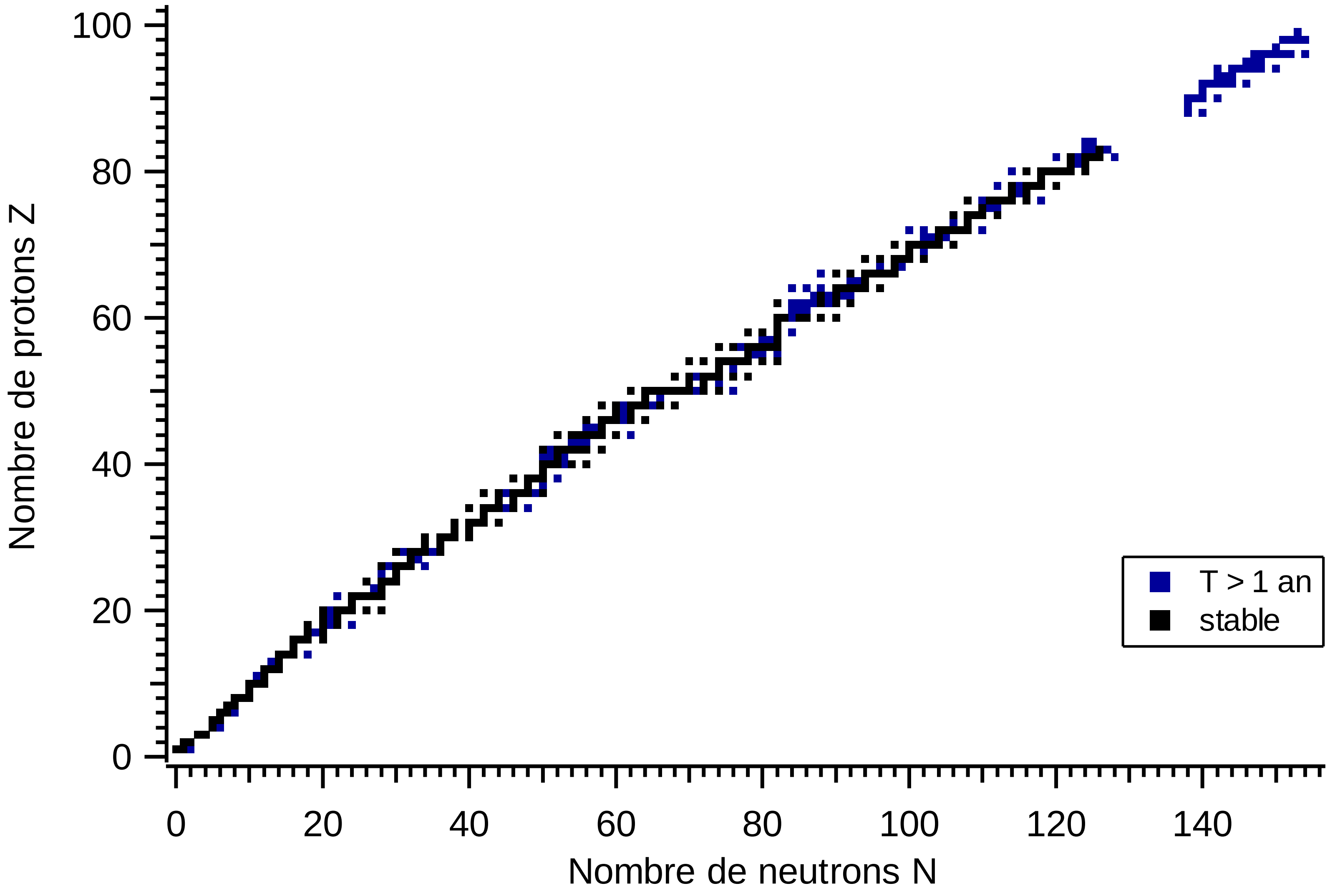


# Stable nuclides

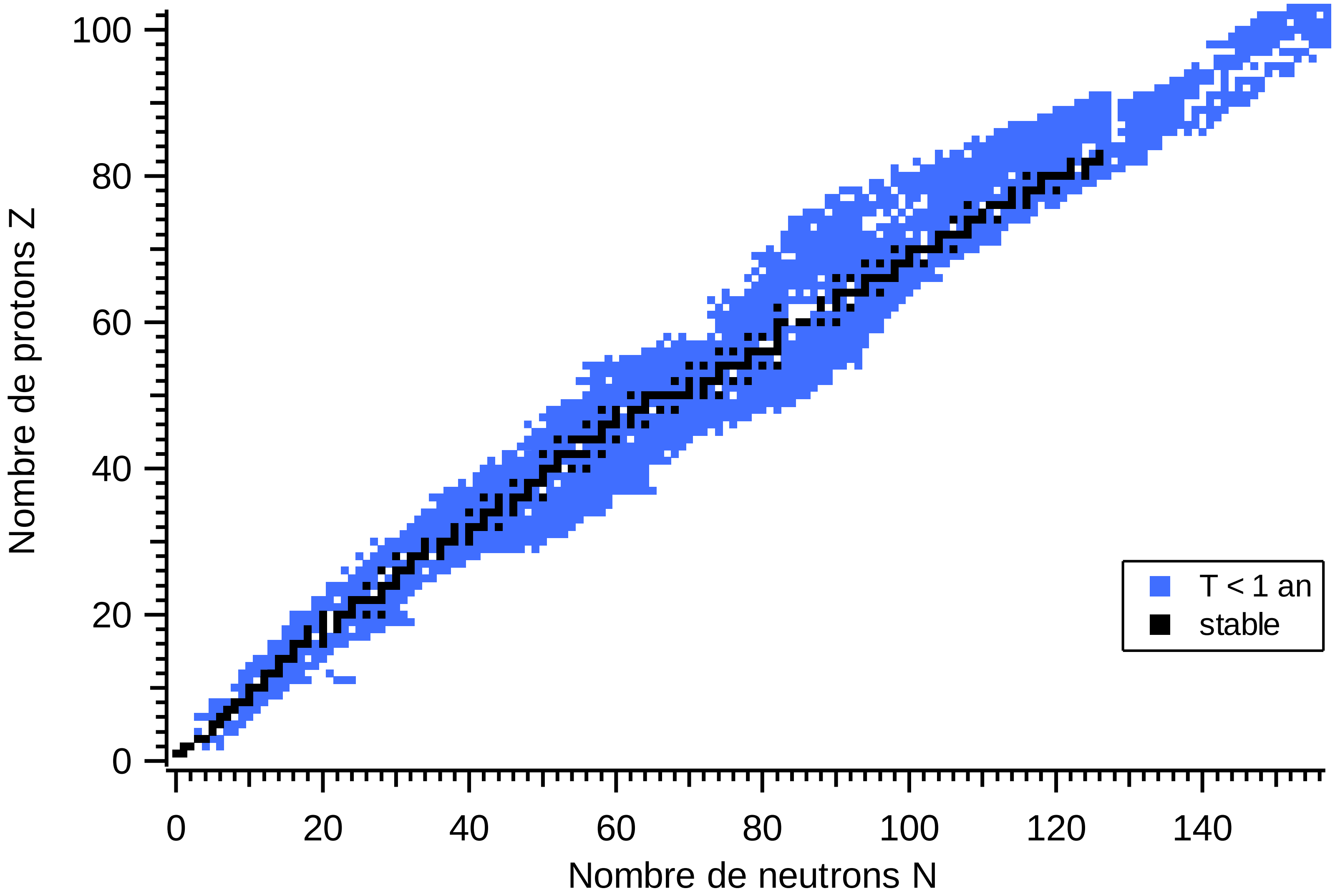
## Nuclide chart



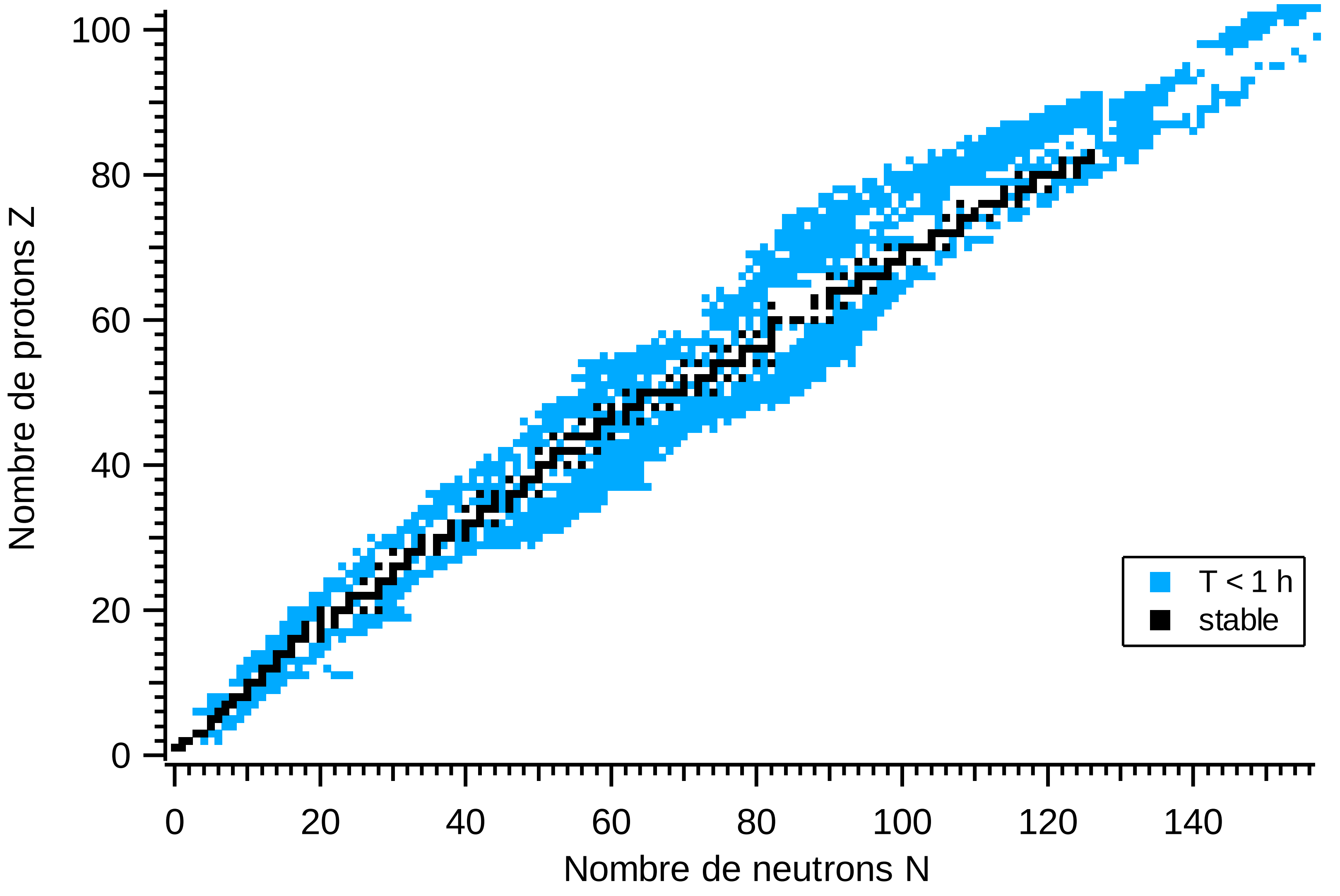
# $T_{1/2}$ > 1 year


100
80
60
40
20
0
Nombre de protons Z
0
20
40
60
80
100
120
140
Nombre de neutrons N
T > 1 an
stable

# $T_{1/2}$ < 1 year

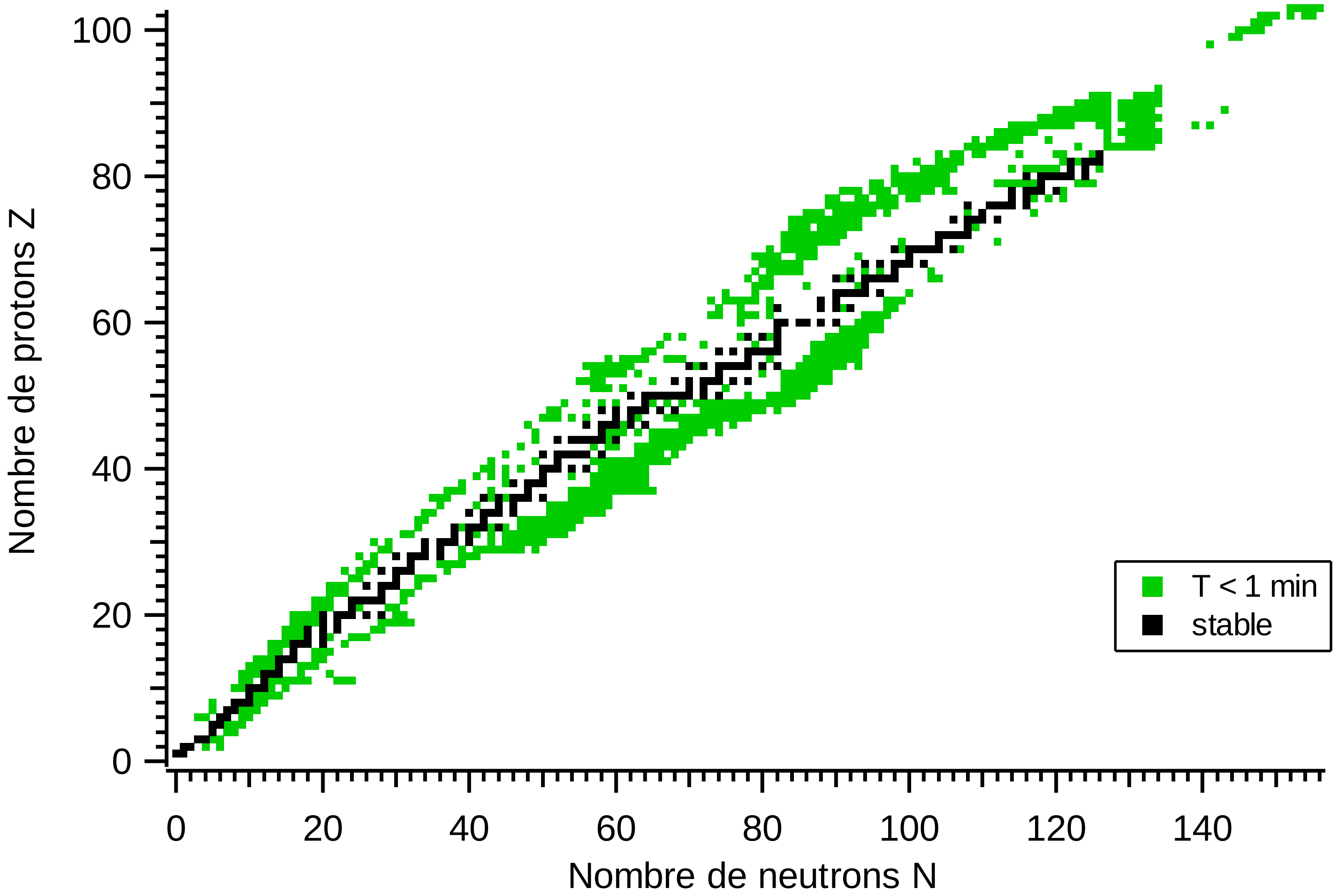

100
80
60
40
20
0
Nombre de protons Z
0
20
40
60
80
100
120
140
Nombre de neutrons N
T < 1 an
stable

# $T_{1/2} < 1$ h



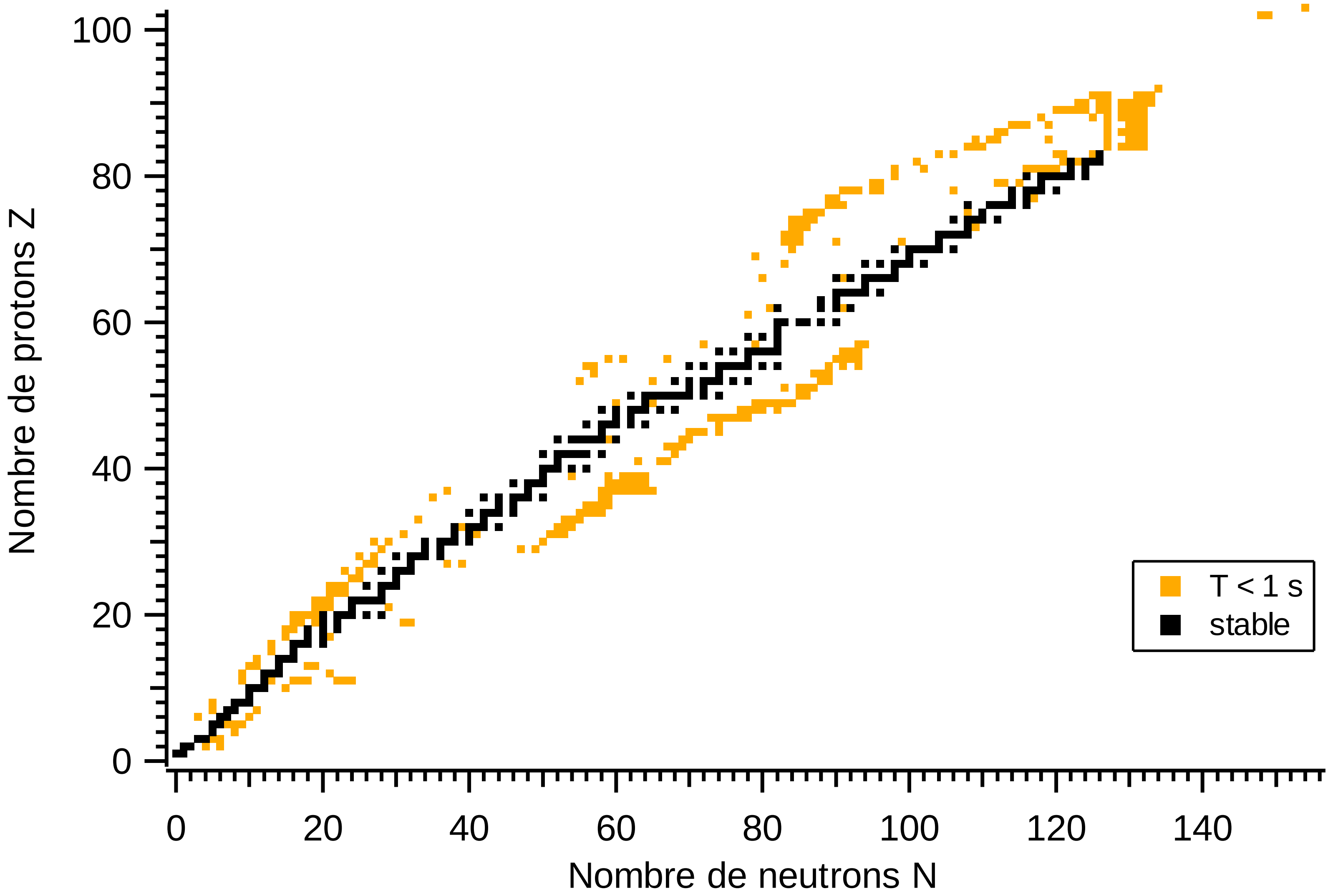
100
80
60
40
20
0
Nombre de protons Z
0
20
40
60
80
100
120
140
Nombre de neutrons N
T < 1 h
stable

# $T_{1/2}$ < 1 min



100
80
60
40
20
0
Nombre de protons Z
0
20
40
60
80
100
120
140
Nombre de neutrons N
T < 1 min
stable

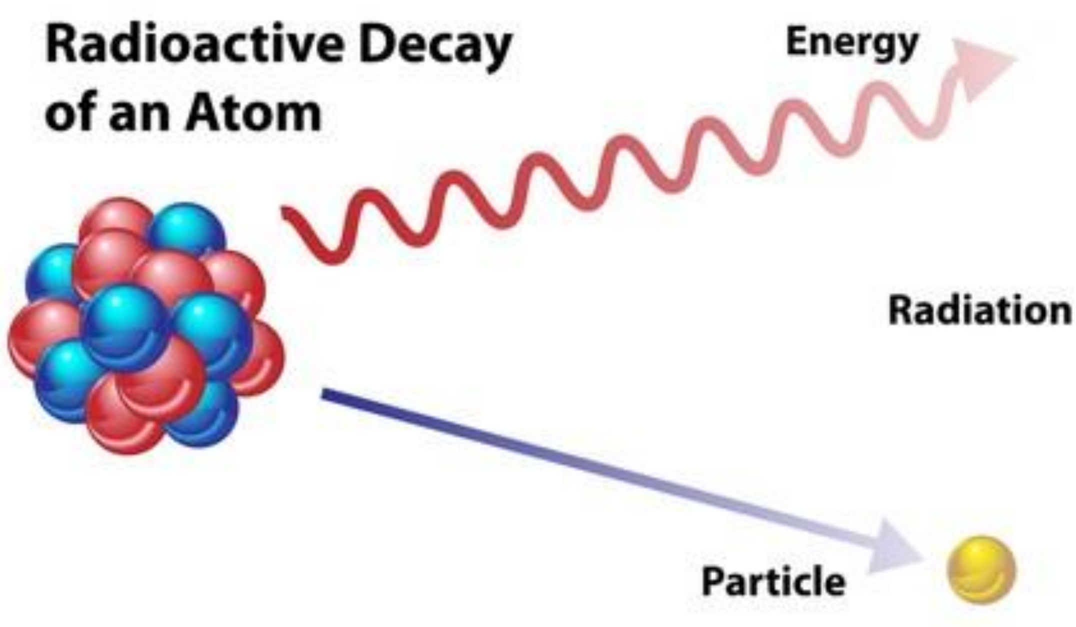
# $T_{1/2} < 1$ s



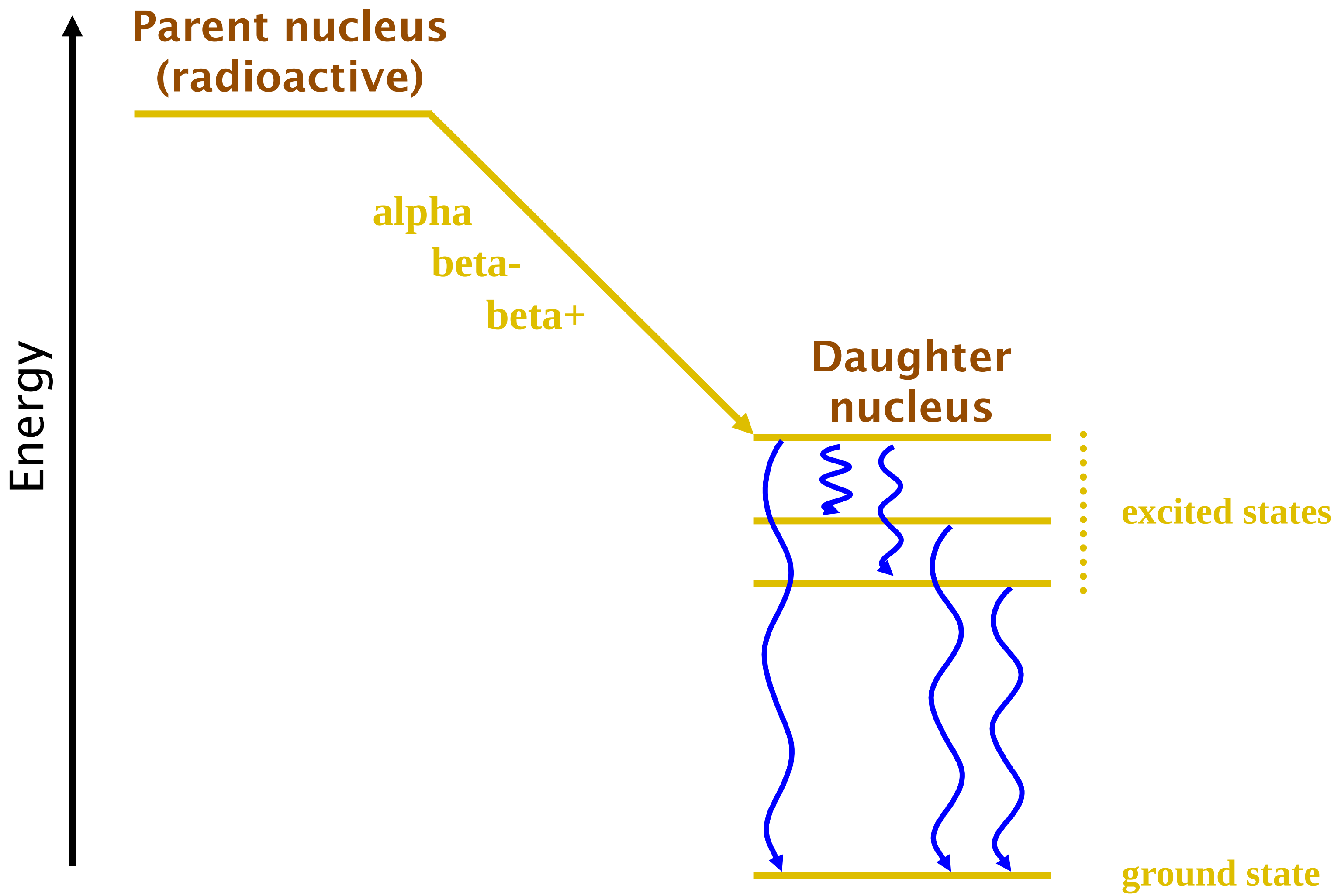
100
80
60
40
20
0
Nombre de protons Z
0
20
40
60
80
100
120
140
Nombre de neutrons N
T < 1 s
stable

# Types of radioactive decay

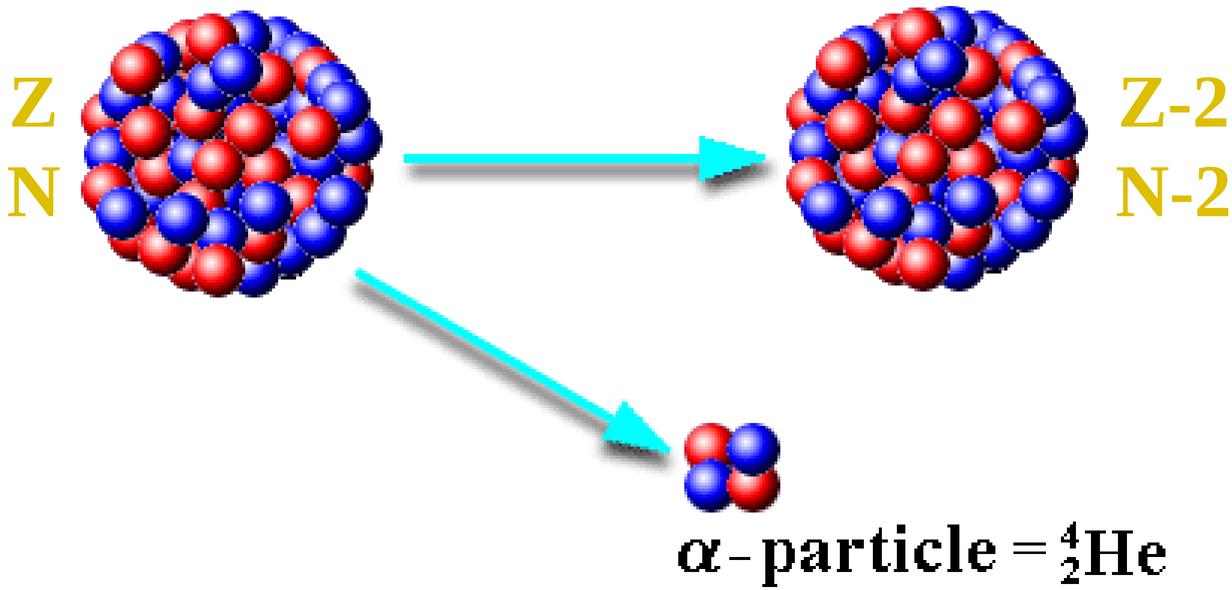
- In which form is the radiation emitted?
- How is the parent nuclide changed?



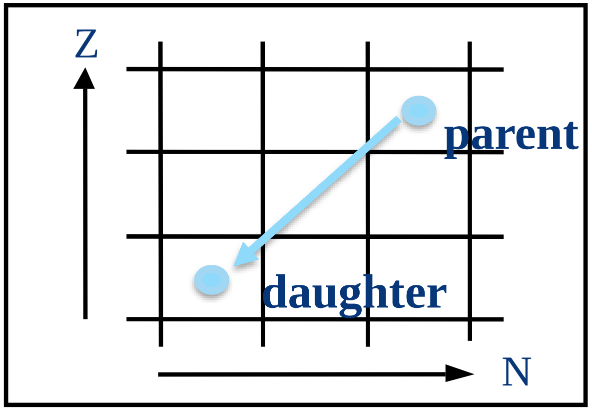
# Decay scheme



# α decay

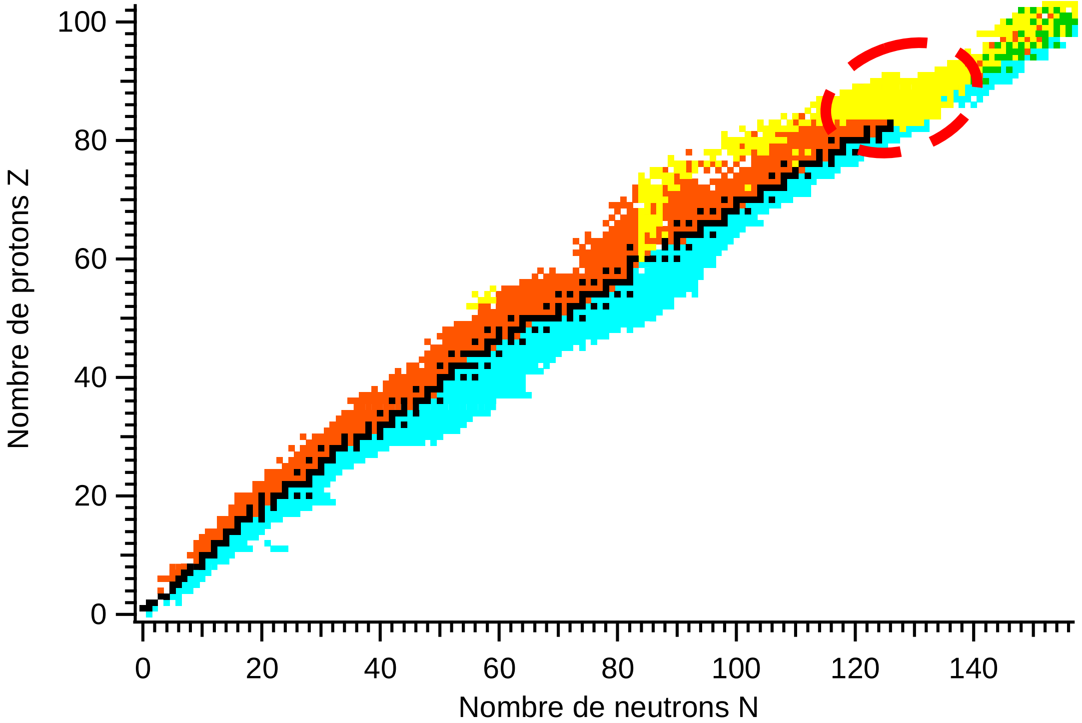


# Nuclide chart: α decay



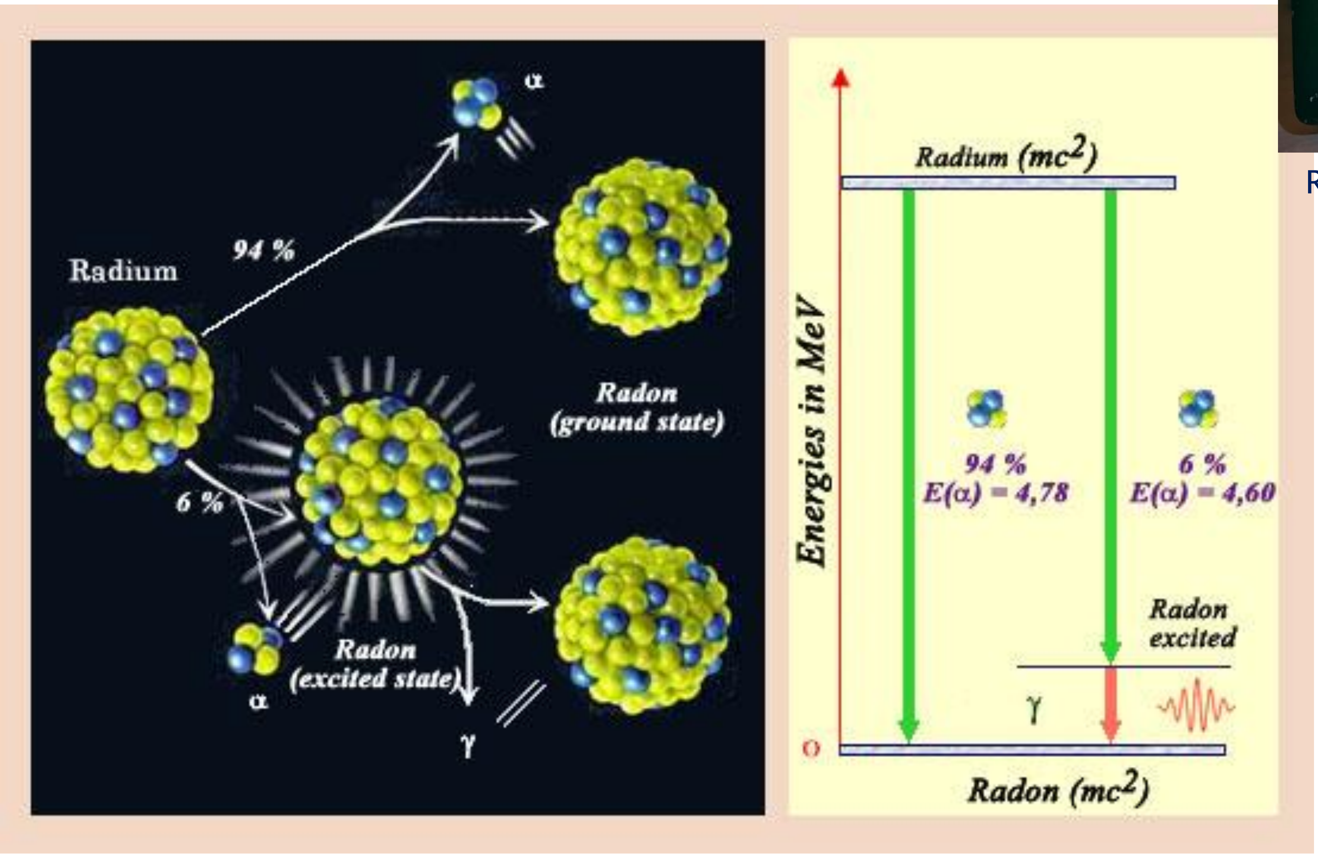

$$ {}^{A}_{Z}E_{N} \rightarrow {}^{A-4}_{Z-2}E_{N-2} + {}^{4}_{2}He_{2} $$

particule α



# α decay

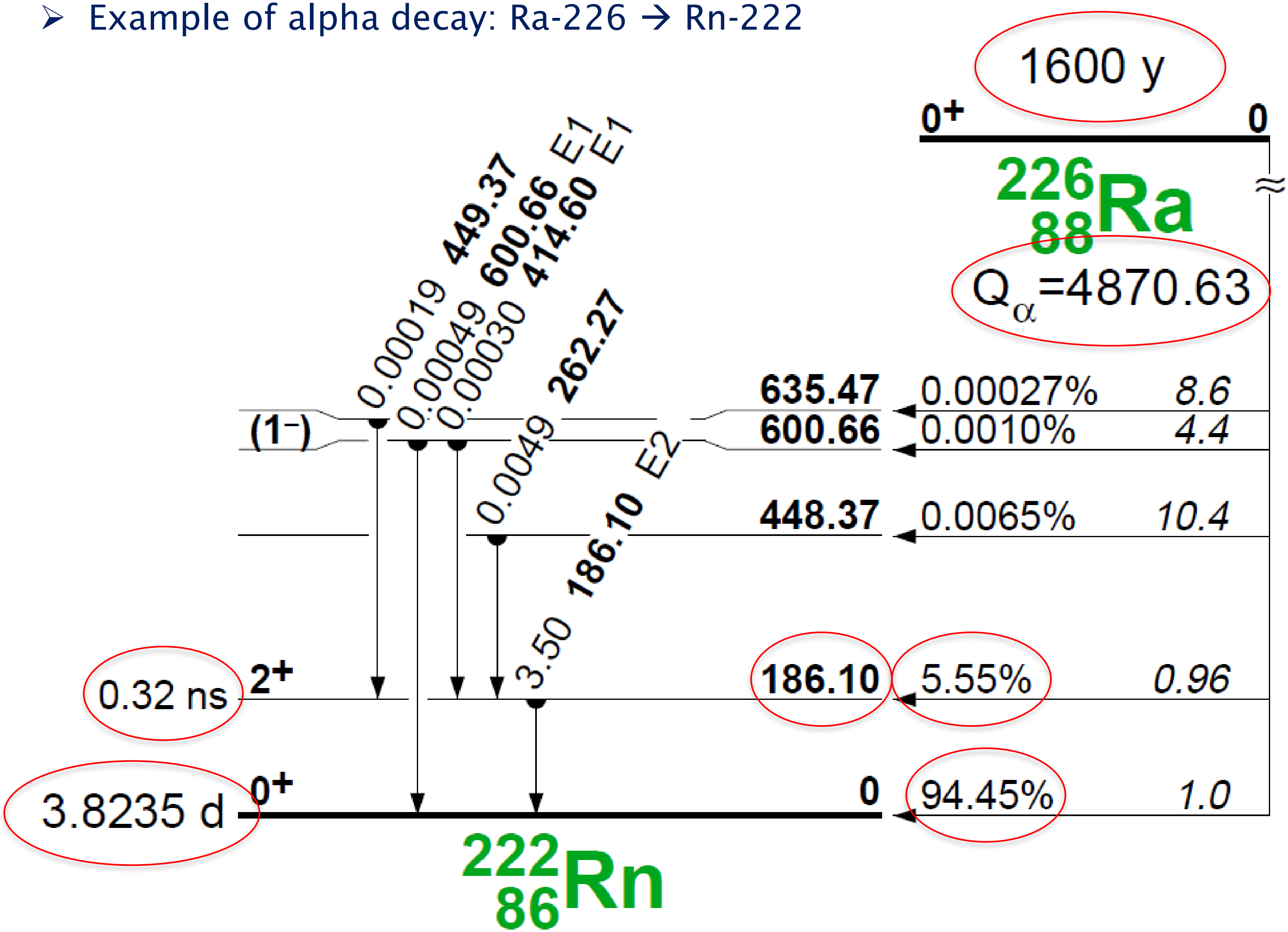
- Example of alpha decay: Ra-226 → Rn-222




Radium dial clock

# α decay

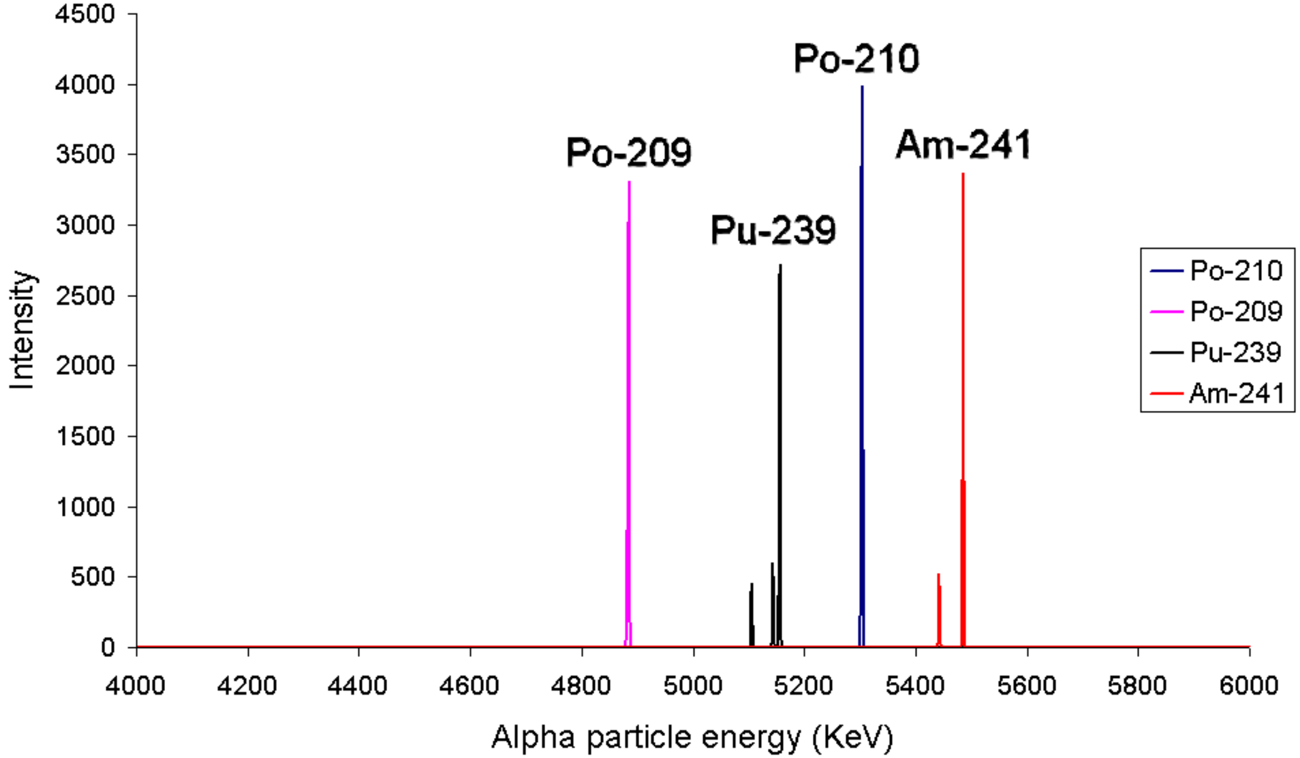
- Example of alpha decay: Ra-226 → Rn-222




R. B. Firestone, Table of Isotopes, Wiley-Interscience, 1996

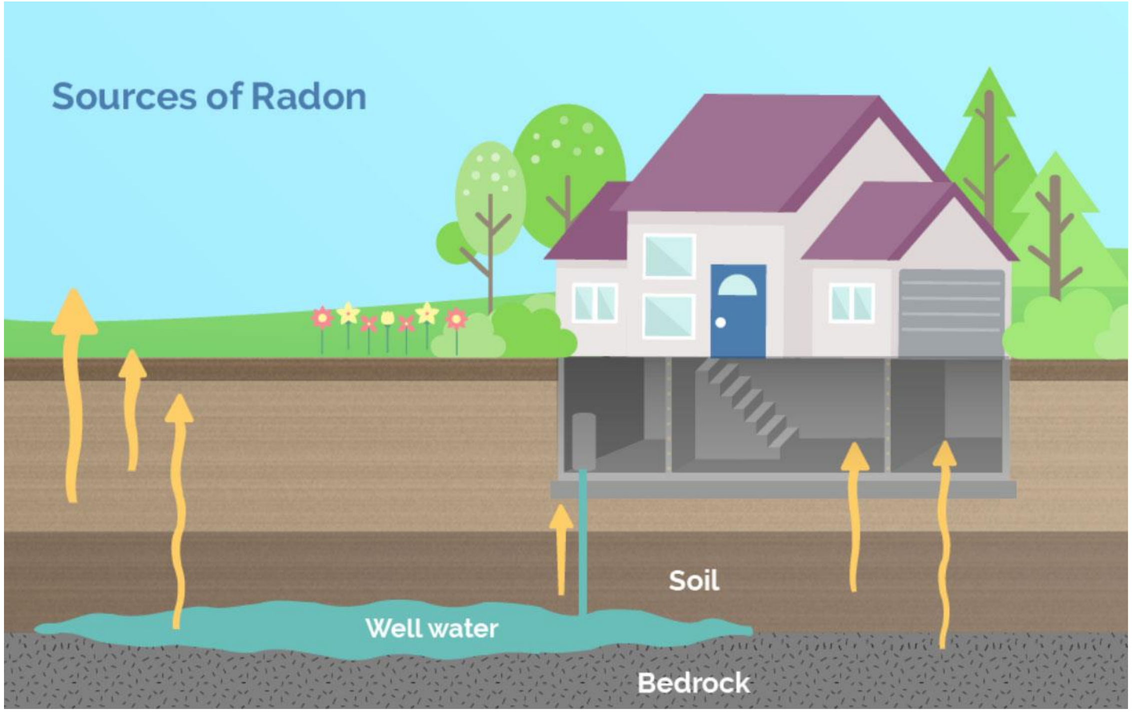
# α decay

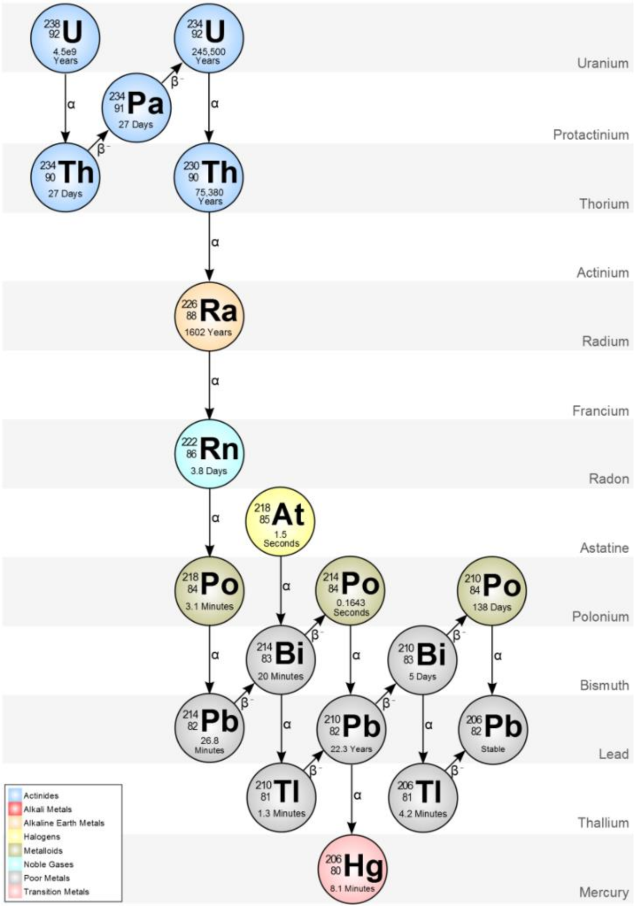
➢ Identification of radionuclides




➢ Alpha decay involves the emission of an alpha particle. The energy spectrum consists of lines that can be used to identify nuclides by spectrometry.

# $^{226}$Ra and $^{222}$Rn are part of $^{238}$U decay chain



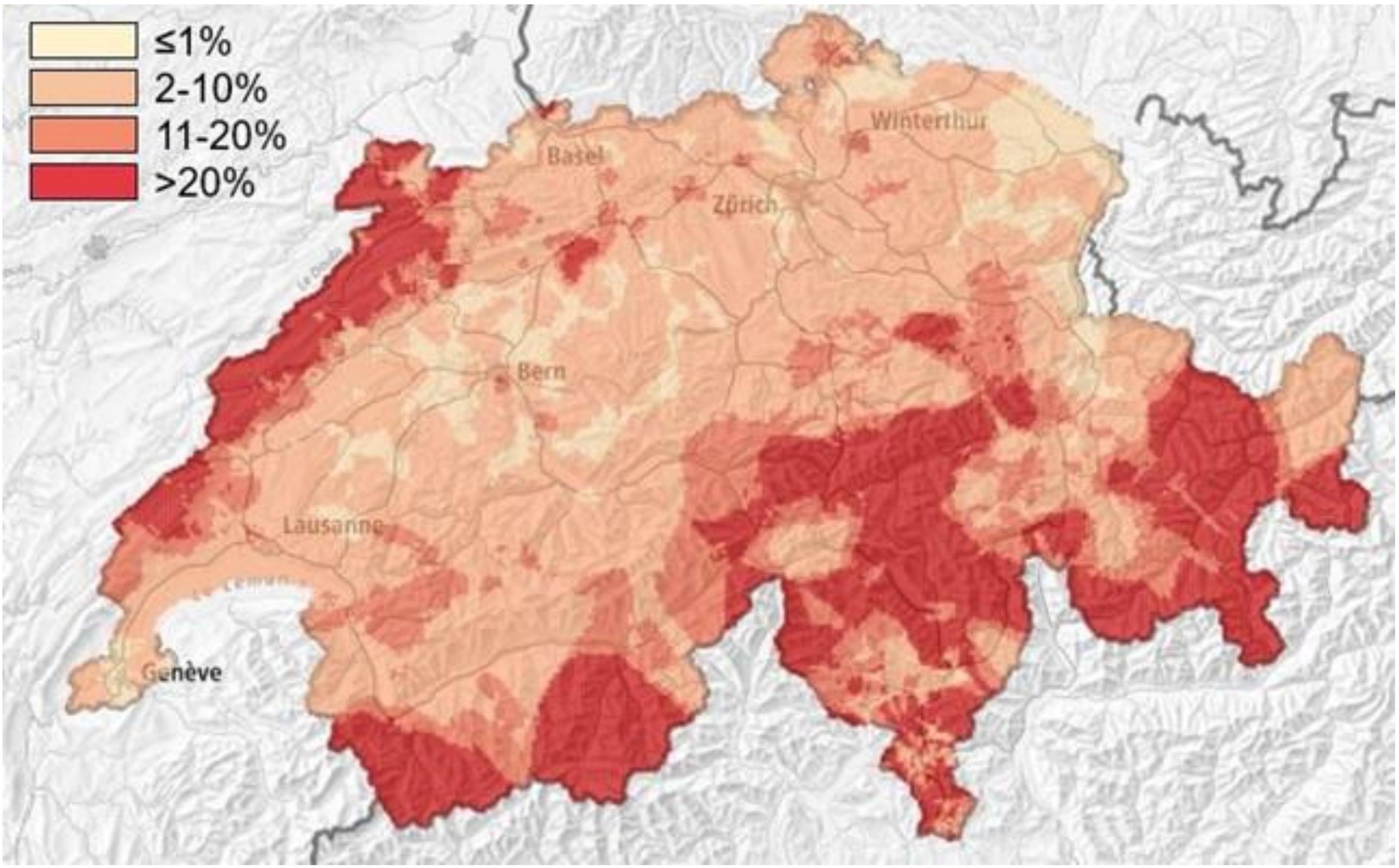




- Exposure to Rn-222 ($T_{1/2}$ = 3.8 days) is the largest naturally occurring environmental hazard

canton de vaud

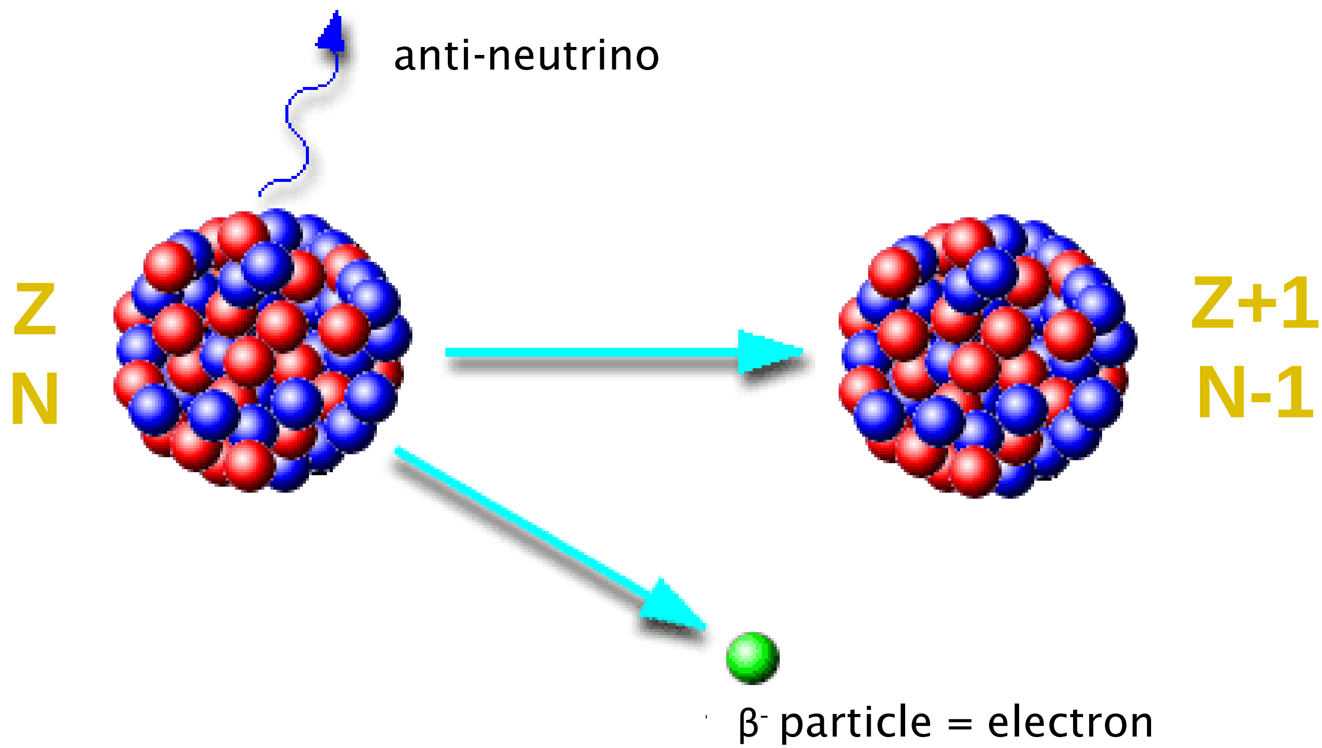
# Radon in Switzerland

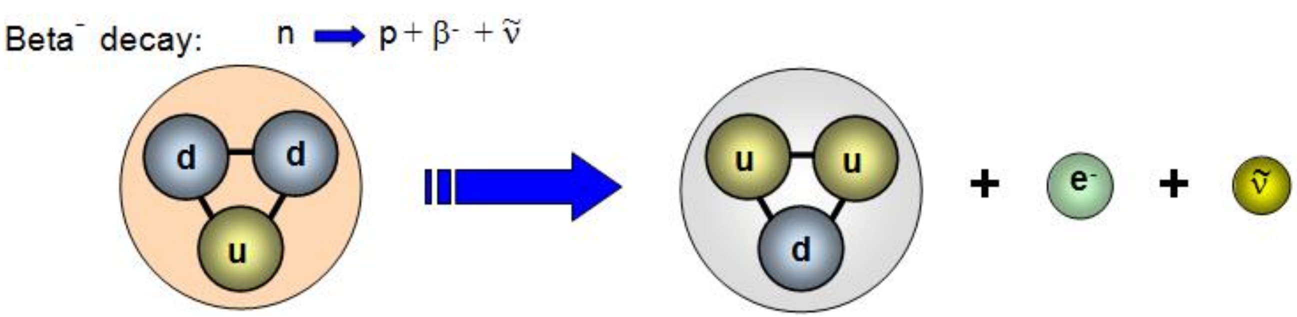
- Probability of exceeding the radon reference value (300 $Bq/m^3$):



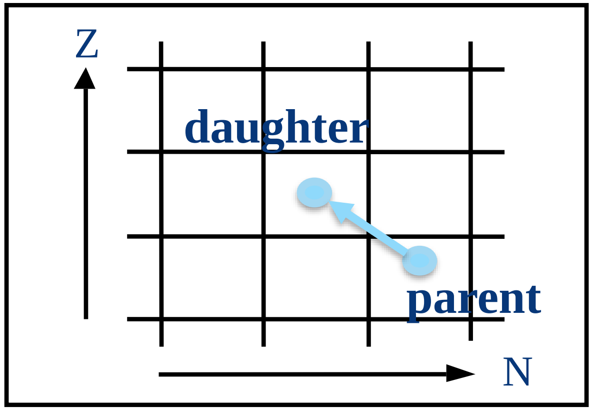

Federal Office of Public Health (FOPH)

# β⁻ decay


anti-neutrino
Z
N
Z+1
N-1
β⁻ particle = electron


Beta⁻ decay: n → p + β- + ν̃
d
d
u
u
u
d
+
e⁻
+
ν̃

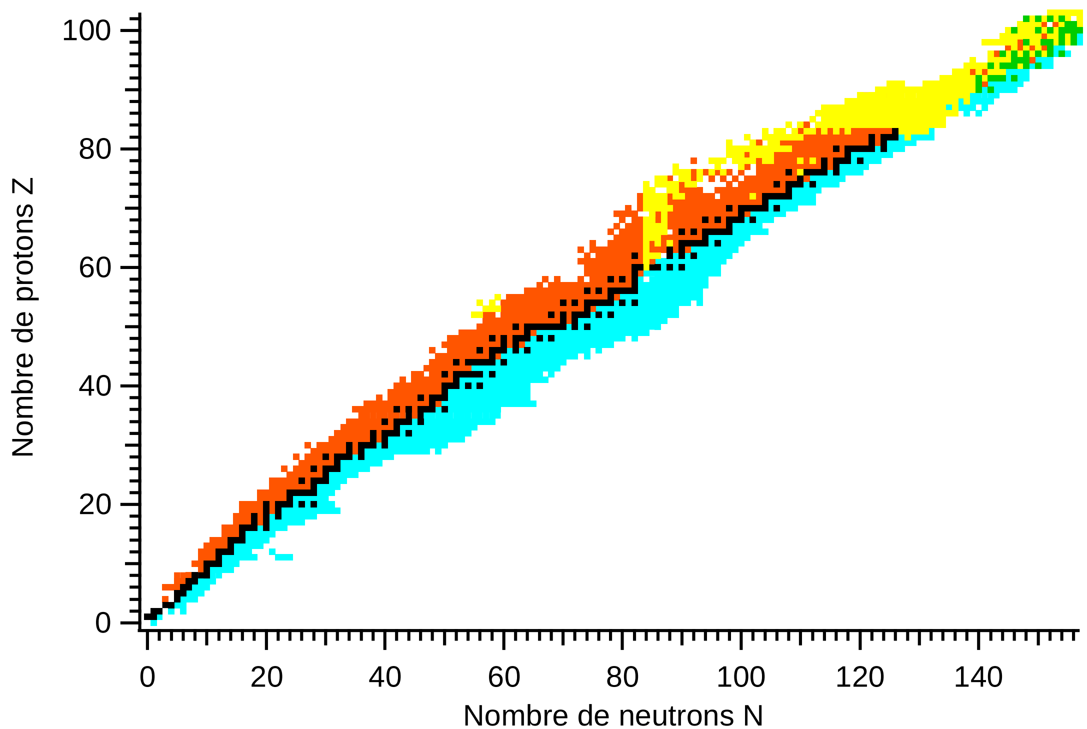
# Nuclide chart: β⁻ decay




$$ {}^{A}_{Z}E_{N} \rightarrow {}^{A}_{Z+1}E_{N-1} + \beta^{-} + \bar{\nu} $$

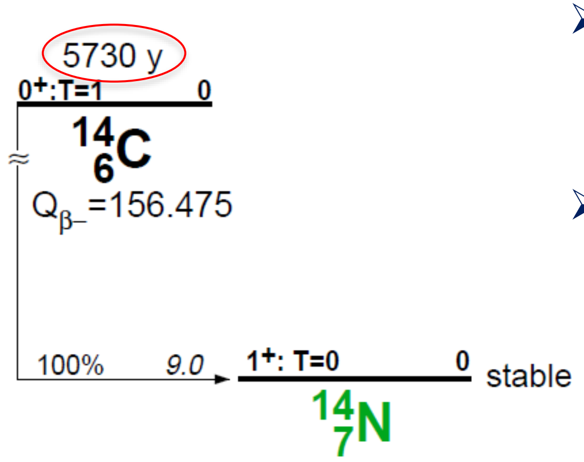
électron　anti-neutrino

- **Neutron** *transforms* into a **proton**

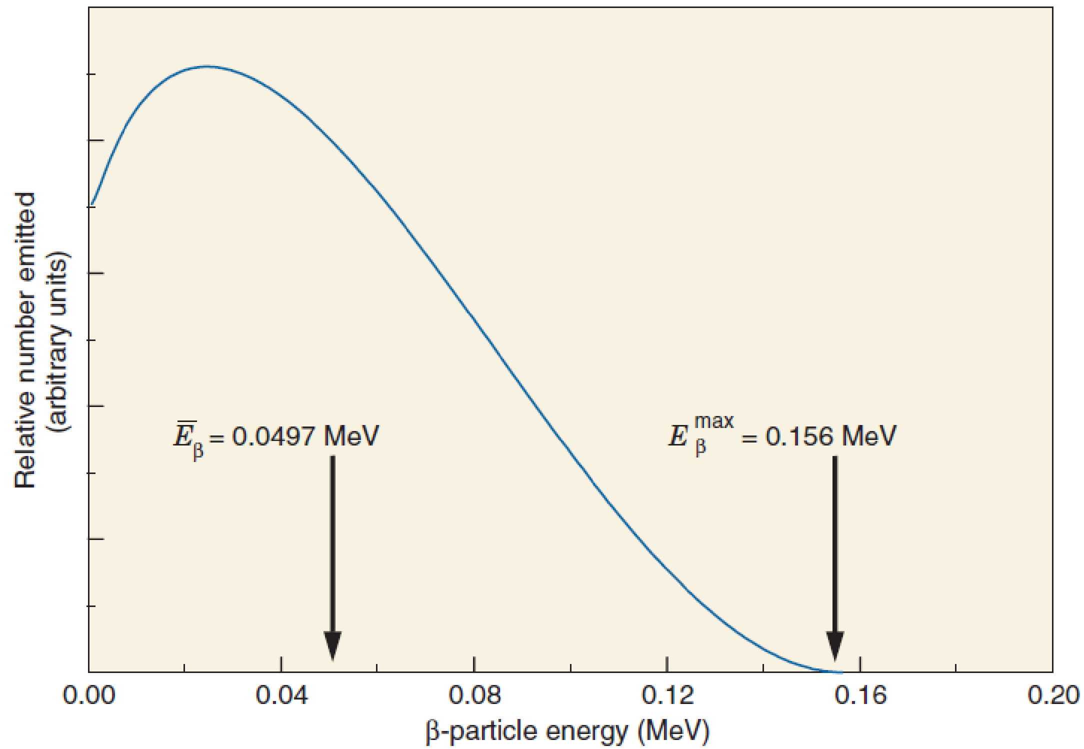


# β⁻ decay

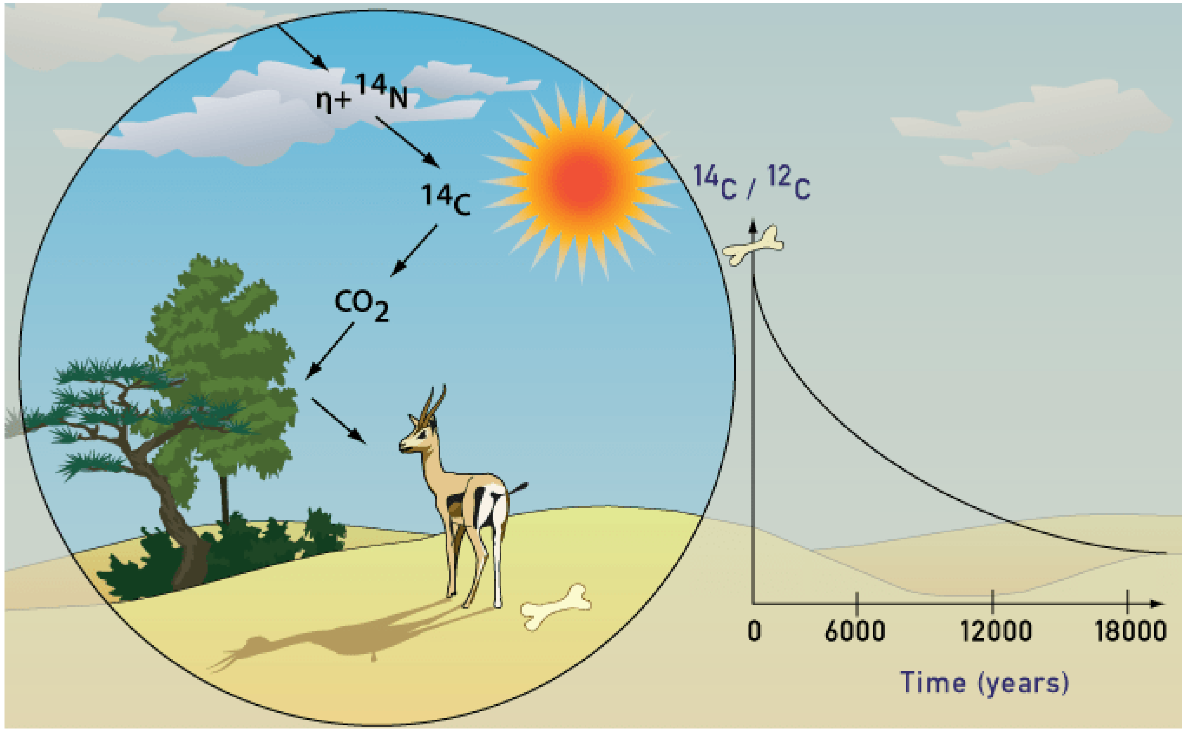
- Example of **β⁻** decay: C-14 → N-14



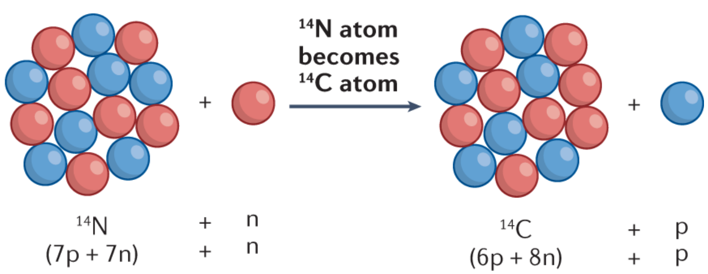

- **β⁻** decay involves the transformation of a neutron into a proton which leads to the emission of an electron and an antineutrino.
- The energy spectrum of **β⁻** particle is continuous:
  - energy is shared between the electron and neutrino



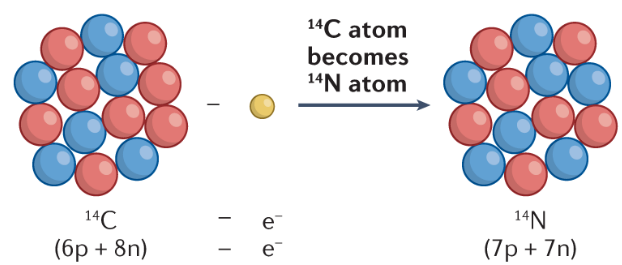
# $^{14}C$ decay is used for carbon dating




## C-14 production:



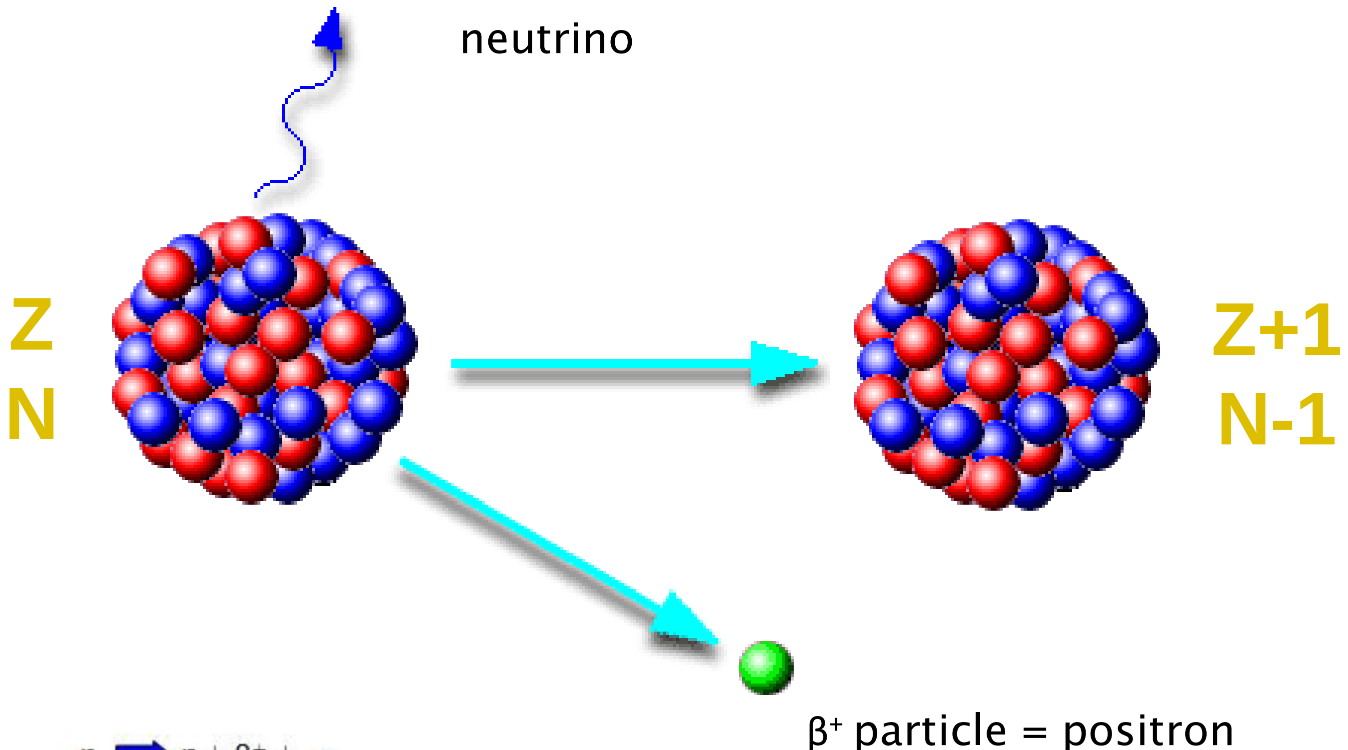

## C-14 decay:

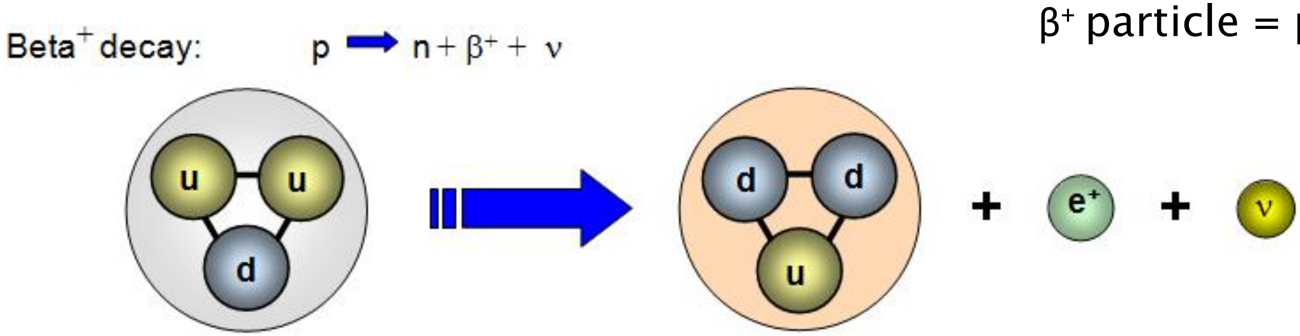


# Carbon dating

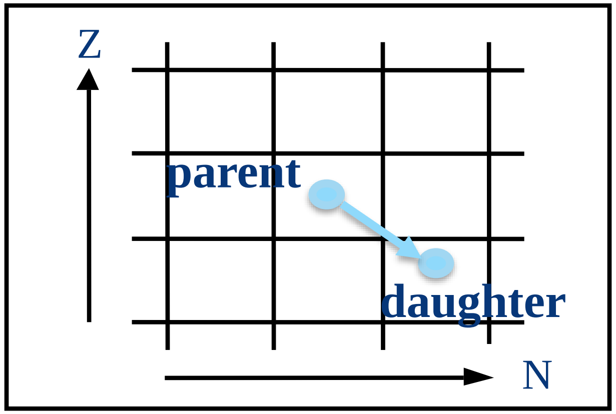
**Q4:** The current disintegration rate for carbon-14 is 14.0 Bq. A sample of burnt wood discovered in an archeological excavation is found to have a carbon-14 disintegration rate of 3.5 Bq. If the half-life of carbon-14 is 5,730 y, approximately how old is the wood sample?

# $\beta^+$ decay


neutrino
Z
N
Z+1
N-1
β+ particle = positron


Beta+ decay: p → n + β+ + ν
u
u
d
d
d
u
+
e+
+
ν

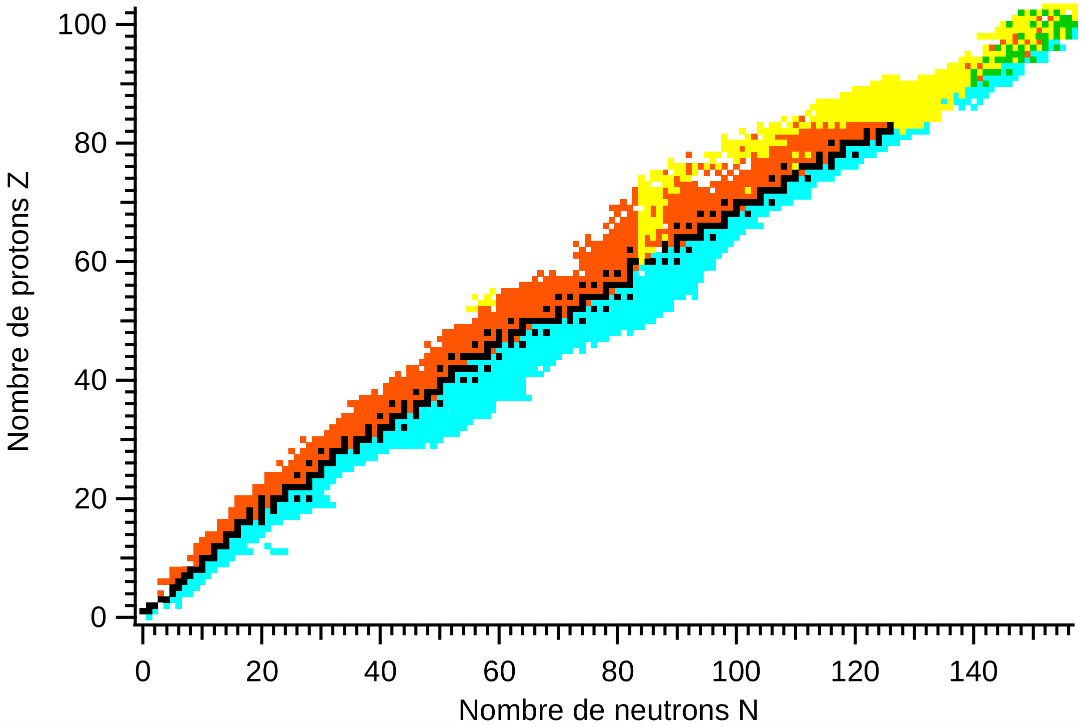
# Nuclide chart: β⁺ decay




$$^{A}_{Z}E_{N} \rightarrow {}^{A}_{Z-1}E_{N+1} + \beta^{+} + \upsilon$$

positron neutrino

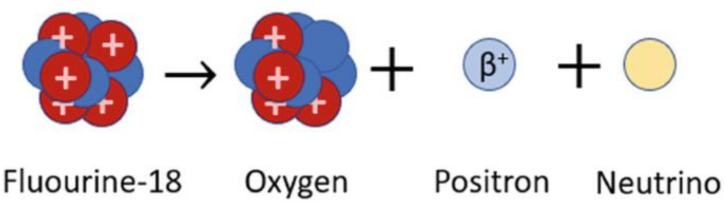
- **Proton** *transforms* into a **neutron**

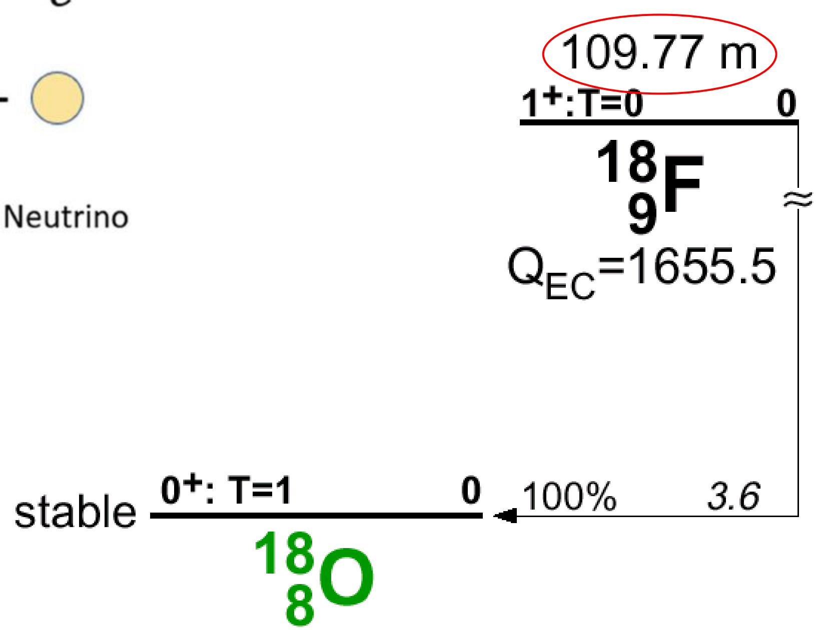


# β⁺ decay

- Example of **β**⁻ decay: F-18 → O-18

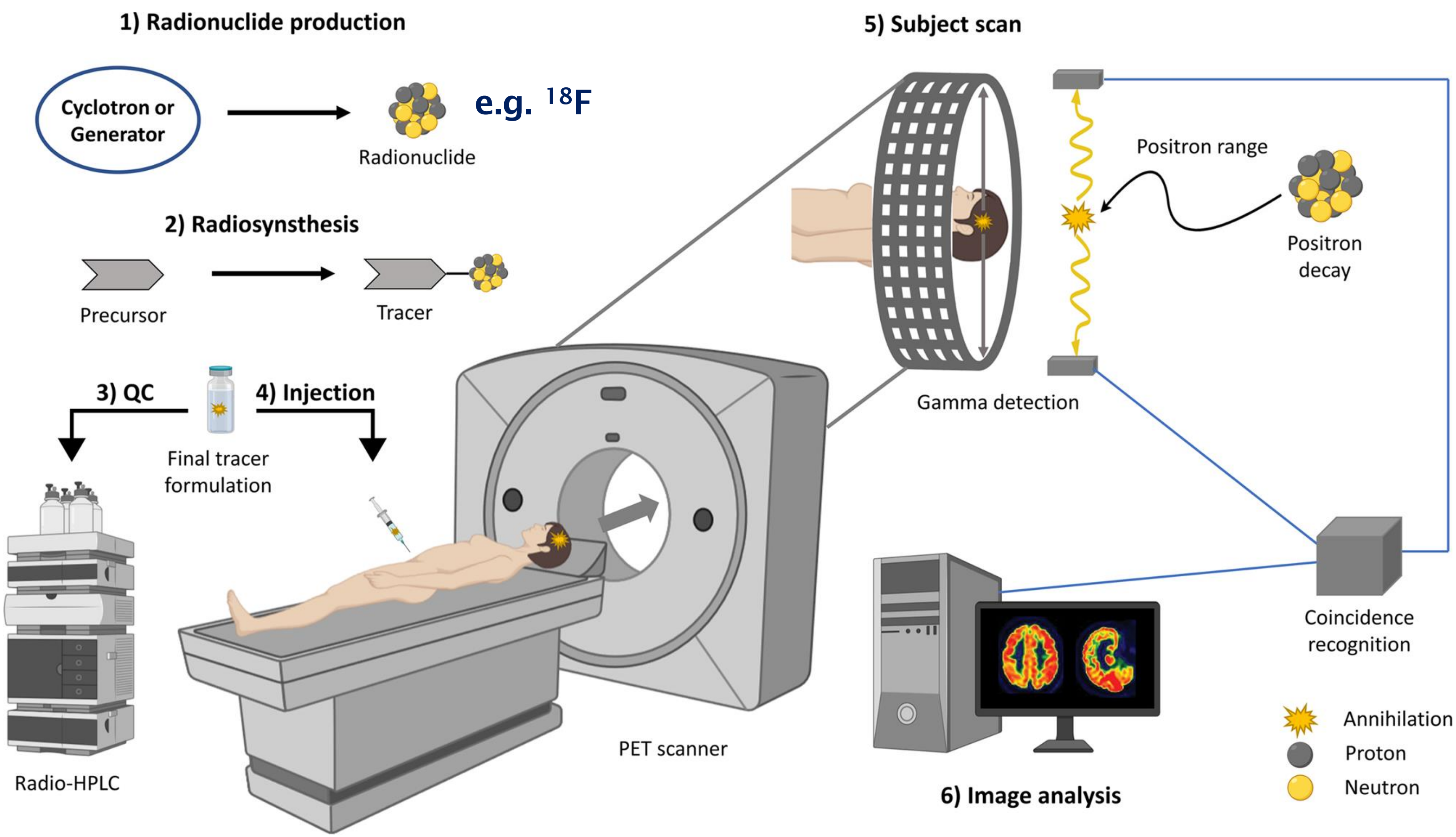
$$ {}^{18}_{9}F \rightarrow {}^{18}_{8}O + e^{+} + \nu_e $$



# Use of β⁺ decay in medicine

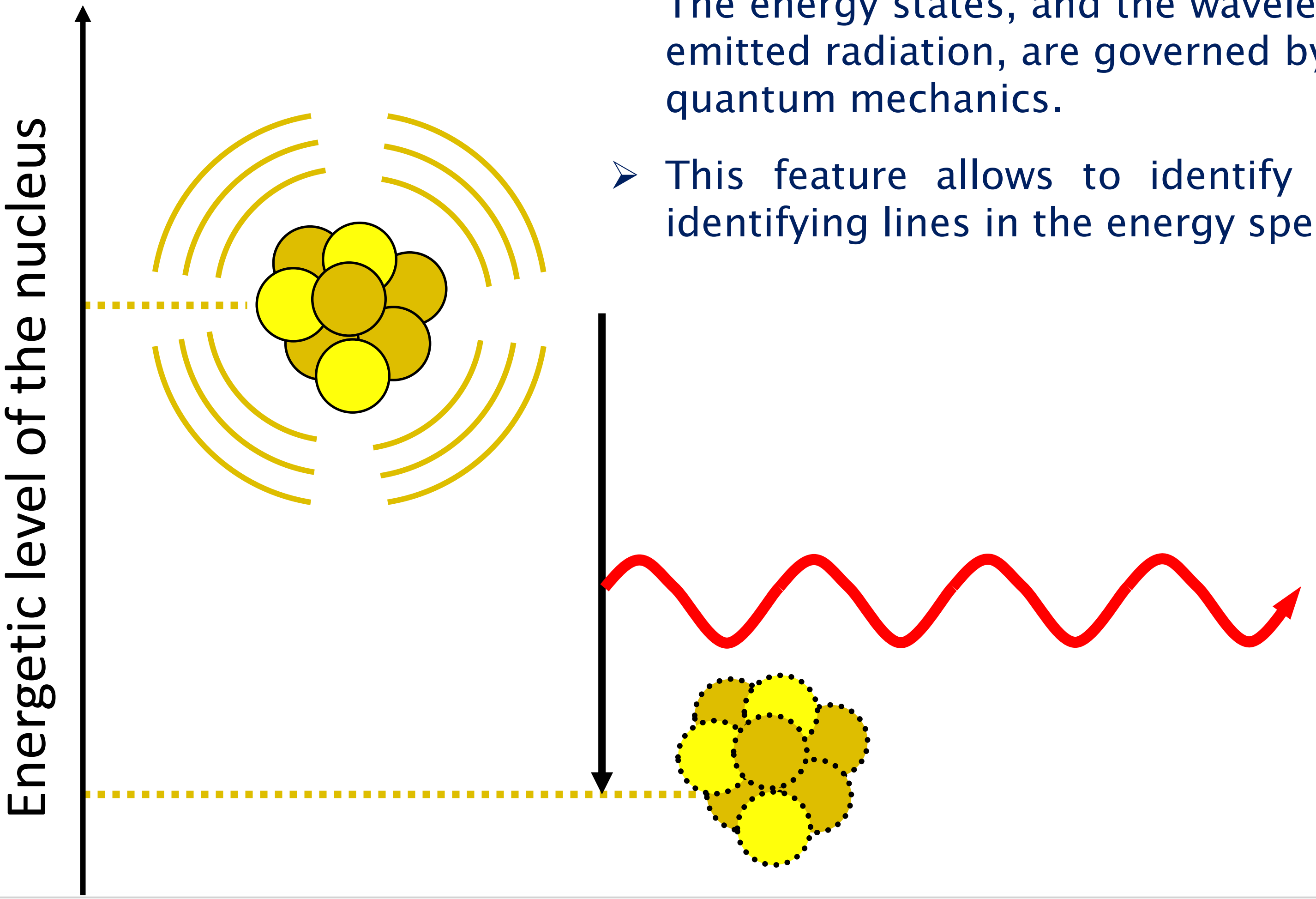
- Positron emission tomography (PET)




*Rong J. et al. Nat. Comm. 2023*

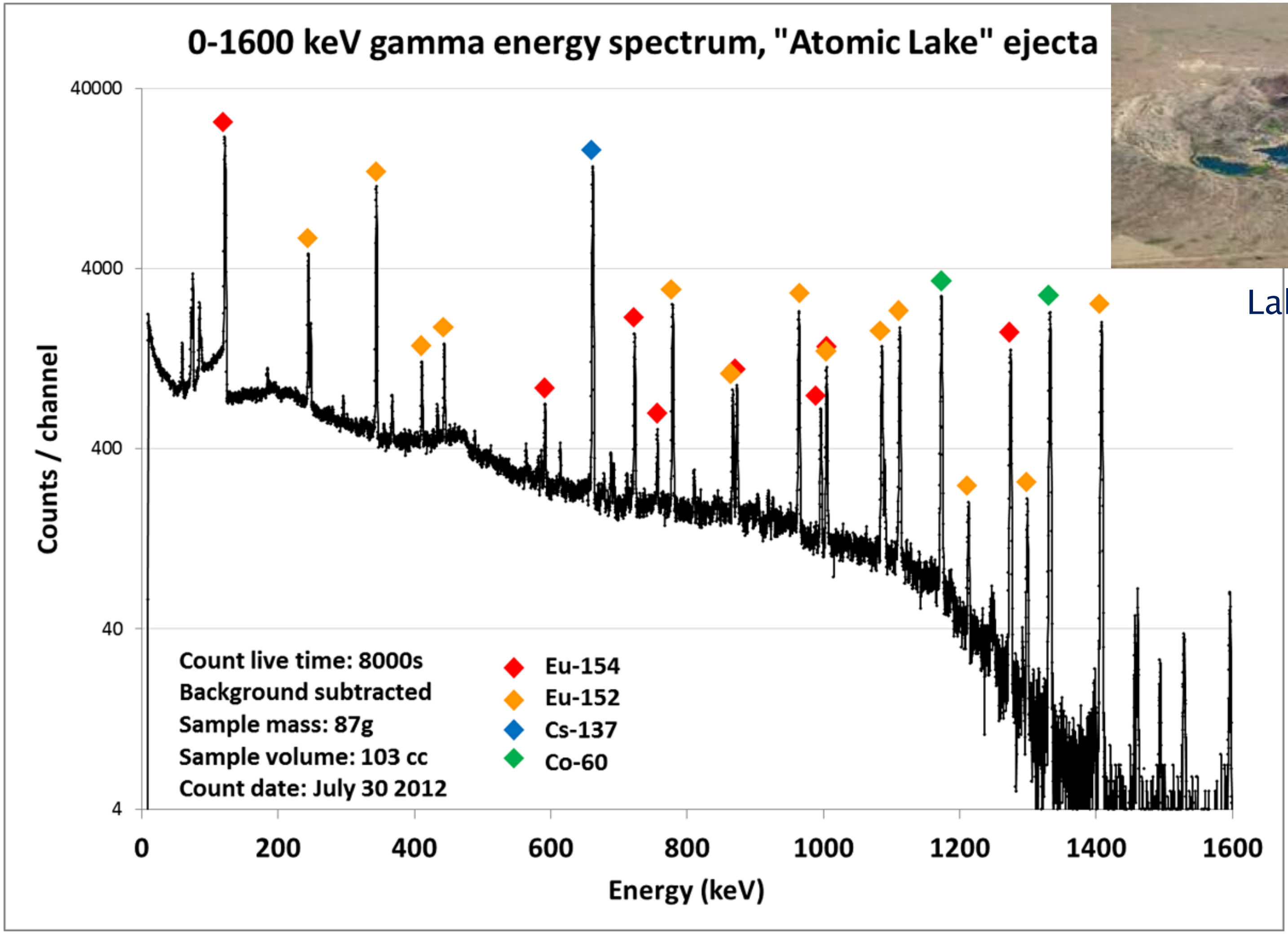
# γ decay

- An atom will stabilize itself by emitting gamma radiation with well defined energies. The energy states, and the wavelengths of the emitted radiation, are governed by the laws of quantum mechanics.
- This feature allows to identify nuclides by identifying lines in the energy spectrum.



# γ decay

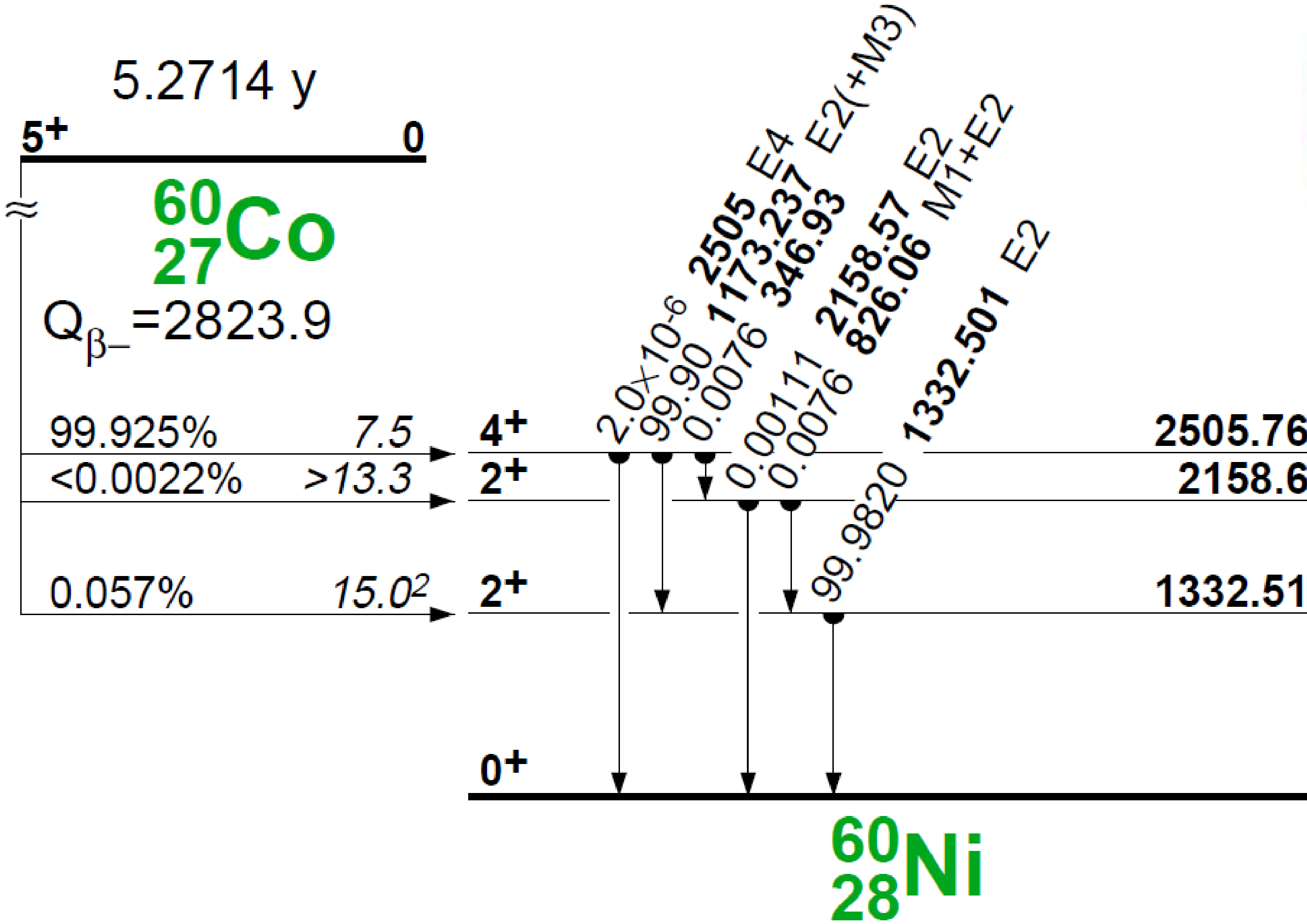
➢ Identification of radionuclides by gamma spectrometry




Lake Chagan

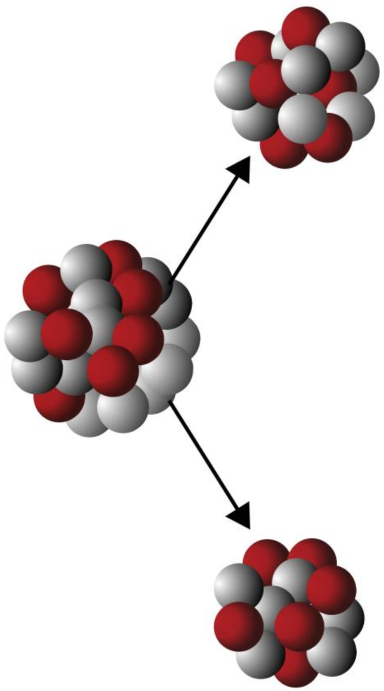
# Radioactive decay

**Q5:** What is the mean number of photons having energies between 1 and 2 MeV emitted after 10'000 decays of Co-60?

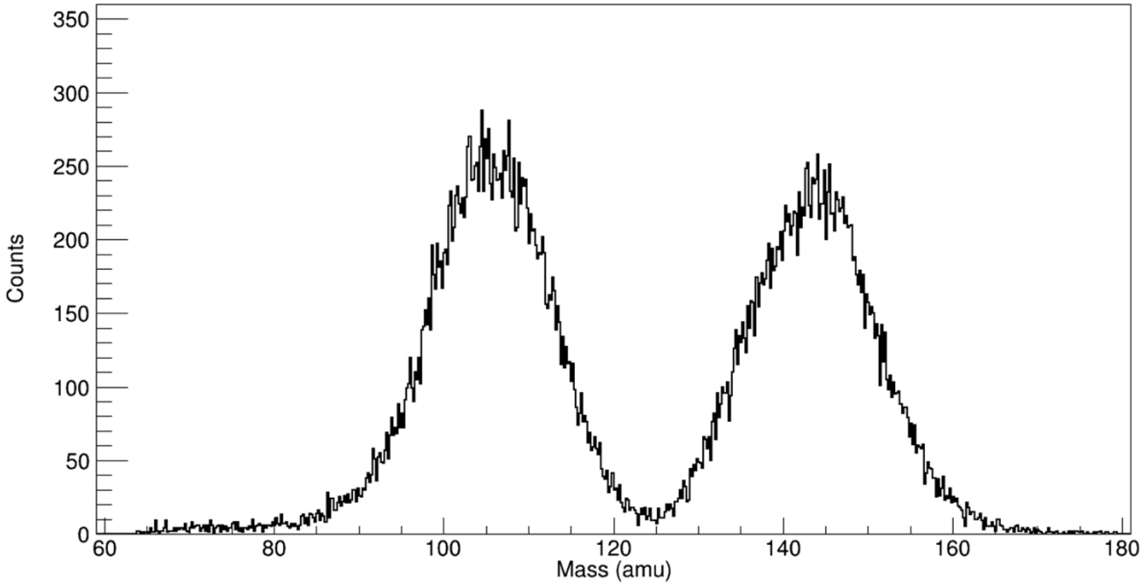



# Fission

- Fission (spontaneous): nucleus of a heavy atom splits into two or more smaller nuclei, along with the release of neutrons and a significant amount of energy

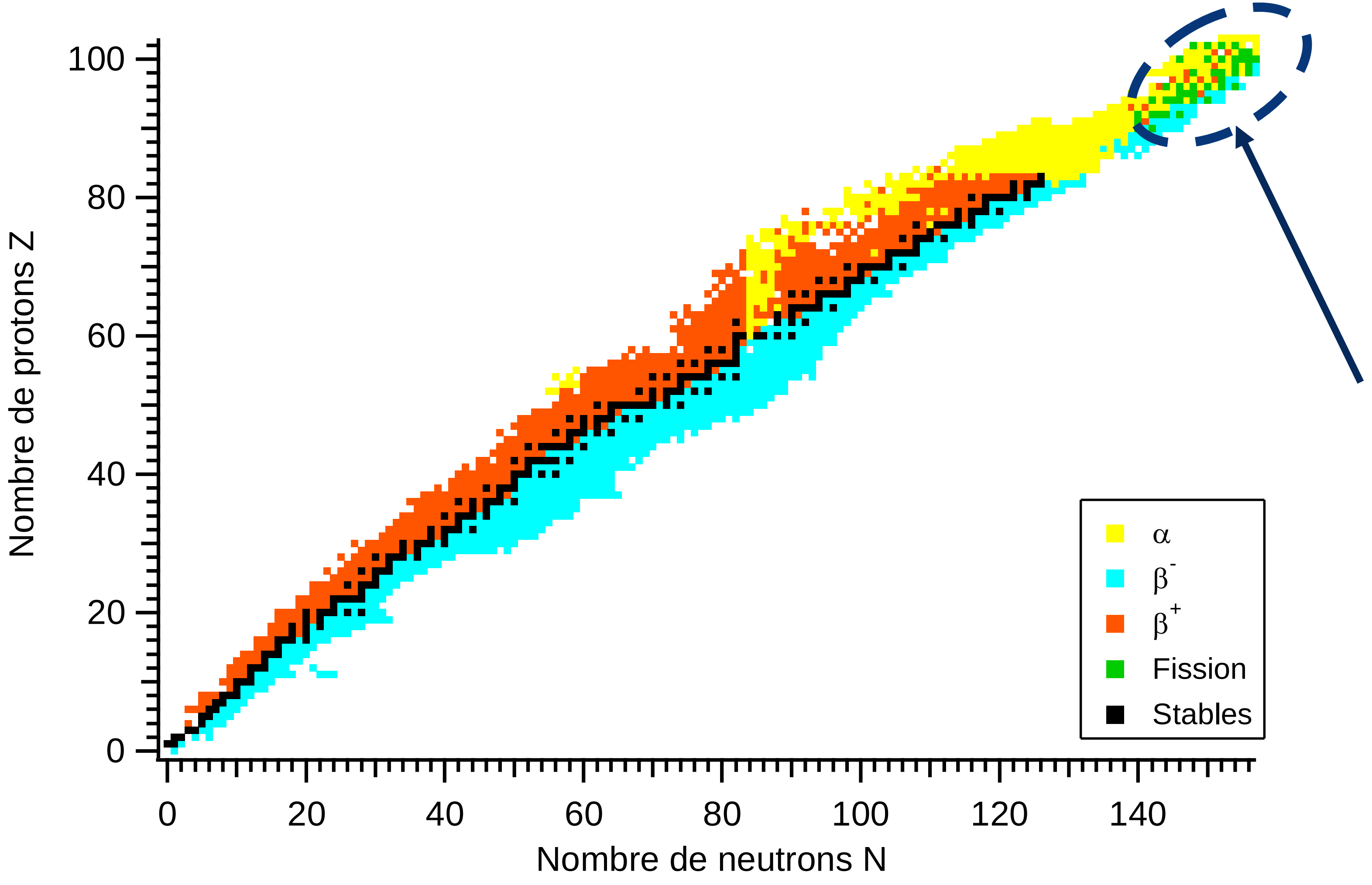


Mass distribution of $^{252}Cf$ spontaneous fission fragments:




- Mass distribution of spontaneous fission fragments is uneven, typically one fragment is heavy and another is light

# Nuclide chart: fission



# Where to find look for information?

## Swiss Radiological Protection Ordinance

*Annexe 3*
(art. 2, al. 1, let. j, l et m, ainsi que 194, al. 3)

**Données pour la radioprotection opérationnelle, limites de libération, limites d'autorisation et valeurs directrices**

Les explications concernant les différentes colonnes et les notes de bas de page sont données sous le tableau.

| | | | Grandeurs d'appréciation | | | | | Limite de libération | Limite d'autorisation | Valeurs directrices | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nucléide | Période | Mode de désintégration / rayonnement | $e_{inh}$ Sv/Bq | $e_{ing}$ Sv/Bq | $h_{10}$ (mSv/h)/ GBq à 1 m de distance | $h_{0,07}$ (mSv/h)/ GBq à 10 cm de distance | $h_{c,0,07}$ (mSv/h)/ (kBq/cm$^2$) | LL Bq/g | LA Bq | CA Bq/m$^3$ | CS Bq/ cm$^2$ | Nucléide de filiation instable |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| H-3, OBT | 12.32 a | β⁻ | 4.10 E-11 | 4.20 E-11 | <0.001 | <1 | <0.1 | 1.E+02 | 1.00 E+08 | 2.00 E+05 | 1000 | |
| H-3, HTO | | β⁻ | 1.80 E-11 | 1.80 E-11 | <0.001 | <1 | <0.1 | 1.E+02 | 3.00 E+08 | 5.00 E+05 | 1000 | |
| H-3, gaz [7] | | β⁻ | 1.80 E-15 | | <0.001 | <1 | <0.1 | | 3.00 E+12 | 5.00 E+09 | | |
| Be-7 | 53.22 d | ec / ph | 4.60 E-11 | 2.80 E-11 | 0.008 | <1 | 0.1 | 1.E+01 | 1.00 E+08 | 2.00 E+05 | 100 | |
| Be-10 | 1.51 E6 a | β⁻ | 1.90 E-08 | 1.10 E-09 | <0.001 | 2000 | 1.6 | 1.E+02 | 3.00 E+05 | 4.00 E+02 | 3 | |
| C-11 | 20.39 min | ec, β⁺ / ph | 3.20 E-12 | 2.40 E-11 | 0.160 | 1000 | 1.7 | 1.E+01 [1] | 7.00E+07 | 7.00 E+04 [3] | 3 | |
| C-11 monoxyde | | | 1.2 E-12 | | | | | | 7.00E+07 | 7.00 E+04 [3] | | |
| C-11 dioxyde | | | 2.2 E-12 | | | | | | 7.00E+07 | 7.00 E+04 [3] | | |
| C-14 | 5.70 E3 a | β⁻ | 5.80 E-10 | 5.80 E-10 | <0.001 | 200 | 0.3 | 1.E+00 | 9.00E+06 | 1.00 E+04 | 30 | |
| C-14 monoxyde | | | 8.00 E-13 | | | | | | 6.00E+09 | 1.00 E+07 | | |
| C-14 dioxyde | | | 6.50 E-12 | | | | | | 8.00E+08 | 1.00 E+06 | | |
| N-13 | 9.965 min | ec, β⁺ / ph | | | 0.160 | 1000 | 1.7 | 1.E+02 [1] | 7.00E+07 | 7.00 E+04 [3] | 3 | |
| O-15 | 122.24 s | ec, β⁺ / ph | | | 0.161 | 1000 | 1.7 | 1.E+02 [1] | 7.00E+07 | 7.00 E+04 [3] | 3 | |
| F-18 | 109.77 min | ec, β⁺ / ph | 9.30 E-11 | 4.90 E-11 | 0.160 | 2000 | 1.7 | 1.E+01 [1] | 7.00E+07 | 7.00 E+04 [3] | 3 | |
| Na-22 | 2.6019 a | ec, β⁺ / ph | 2.00 E-09 | 3.20 E-09 | 0.330 | 2000 | 1.6 | 1.E-01 | 3.00E+06 | 4.00 E+03 | 3 | |
| Na-24 | 14.9590 h | β⁻ / ph | 5.30 E-10 | 4.30 E-10 | 0.506 | 1000 | 1.9 | 1.E+00 | 9.00E+06 | 2.00 E+04 | 3 | |
| Mg-28 / Al-28 | 20.915 h | β⁻ / ph | 1.70 E-09 | 2.20 E-09 | 0.529 | 2000 | 3.1 | 1.E+01 [2] | 3.00E+06 | 5.00 E+03 | 3 | |
| Al-26 | 7.17 E5 a | ec, β⁺ / ph | 1.40 E-08 | 3.50 E-09 | 0.382 | 1000 | 1.5 | 1.E-01 | 4.00E+05 | 6.00 E+02 | 3 | |

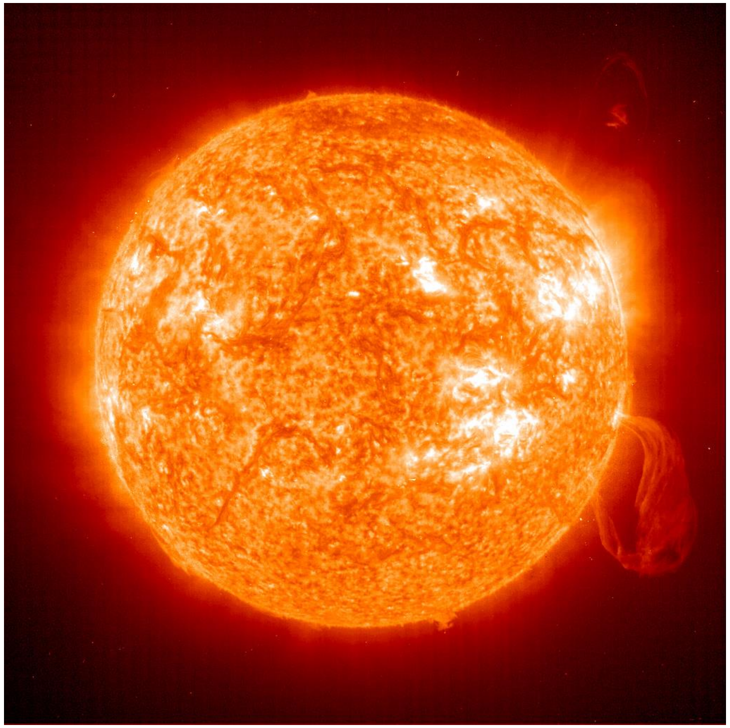
# Primordial radionuclides

- Primordial radionuclides are here since the beginning of the Earth (4.5 billion years):

  Uranium-238 ($T_{1/2}$=4.5 billion years)

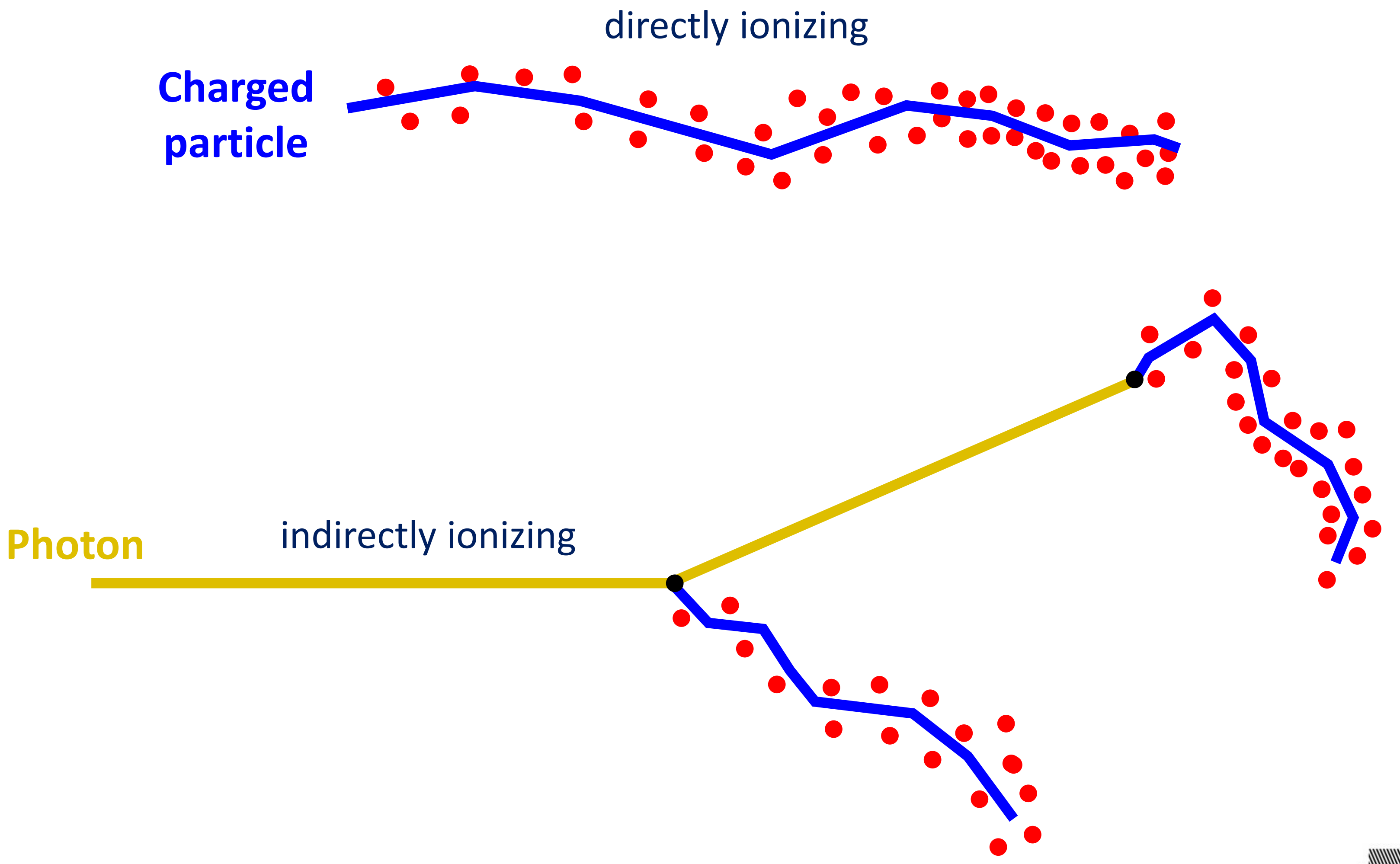
  Thorium 232 ($T_{1/2}$=14 billion years)

  Potassium-40 ($T_{1/2}$=1.2 billion years)




- They are the primary sources of natural background radiation

# Interaction of radiation with matter



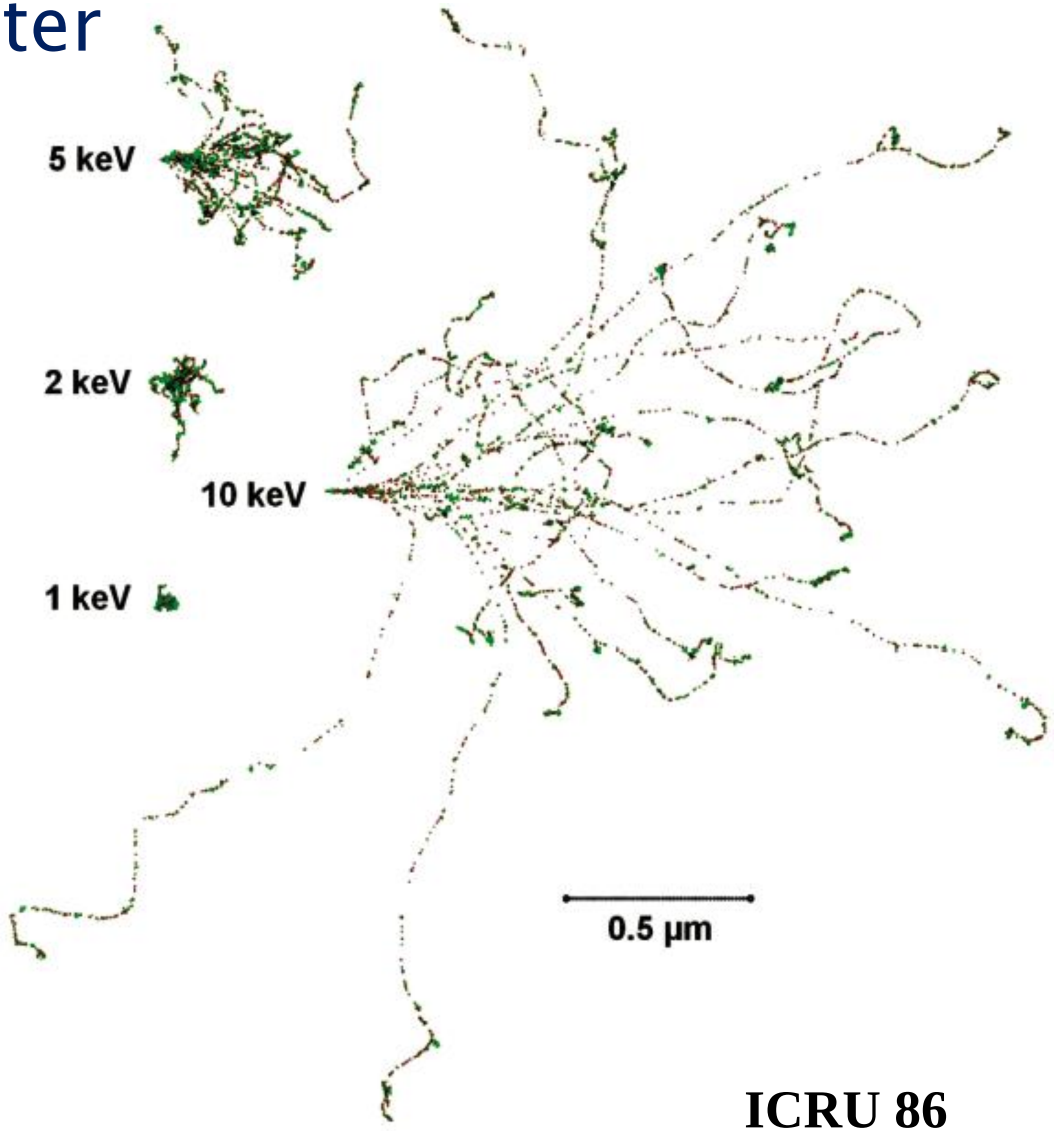

canton de vaud

CHUV

# Electron tracks in matter

- Electrons interact mainly with other electrons inside the matter and produce "**zigzag" trajectories**
- Large dispersion of traces

Explanation: collisions between particles of same masses

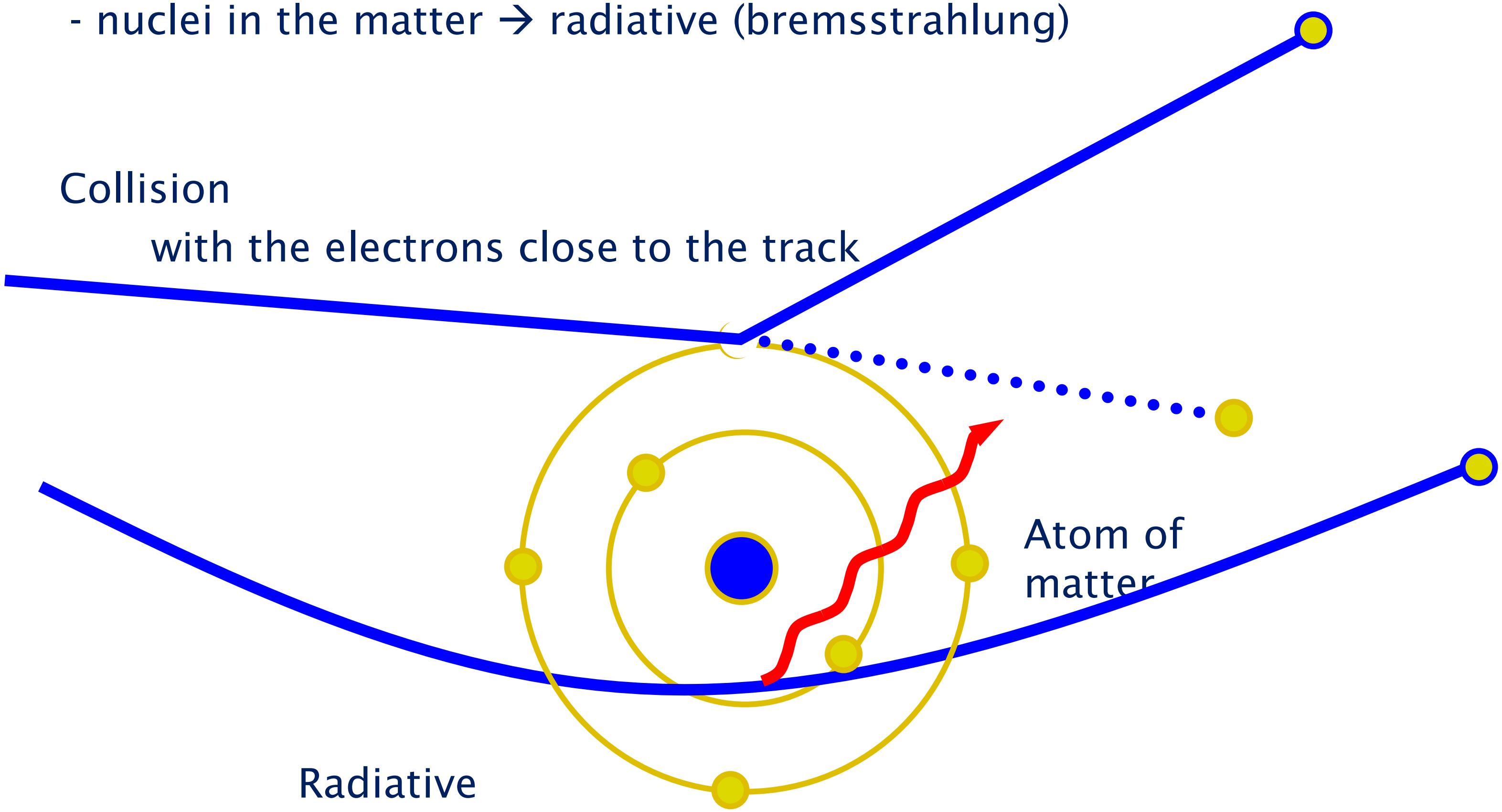



**ICRU 86**

Figure 2.3. Twenty randomly generated electron tracks for initial kinetic energies of 1 keV, 2 keV, 5 keV, and 10 keV. Red points represent ionizations, and green points represent excitations. All tracks of the same energy start at the same point and initially proceed in the same direction (left to right in the figure).

# Interaction of electrons with matter

- An electron can be slowed down by Coulomb interaction with:
  - other electrons in the matter → collision
  - nuclei in the matter → radiative (bremsstrahlung)



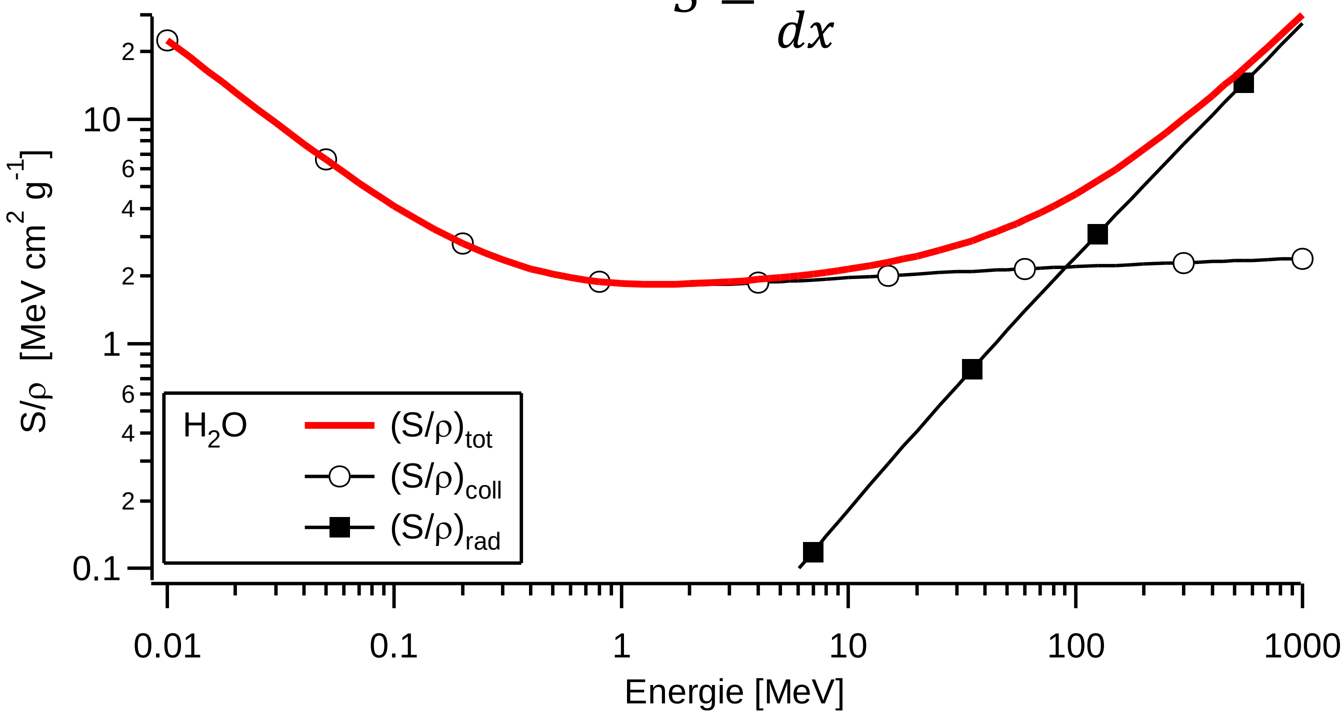

photon emission in the nucleus vicinity (bremsstrahlung)

# Stopping power of electrons in water

**Stopping power**

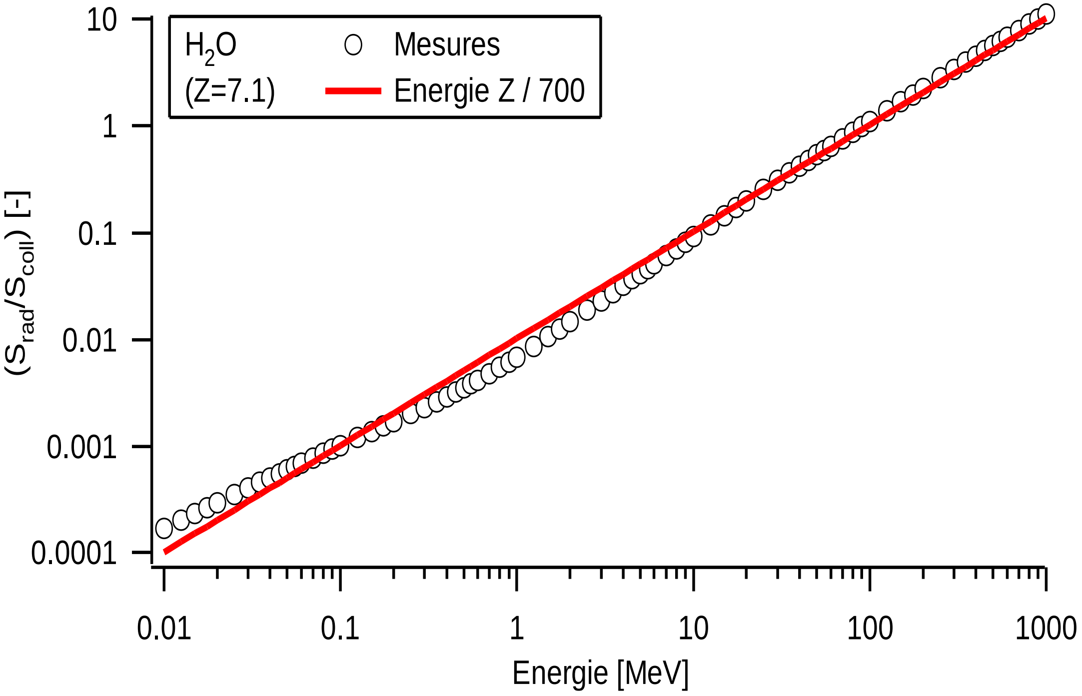
The stopping power of a material for a particle is the amount of energy that it loses per unit length along its path. The mass stopping power is stopping power normalized to the density ρ of the material

$$S = \frac{dE}{dx}$$



# Radiative vs. Collision stopping

## Dependace on electron energy

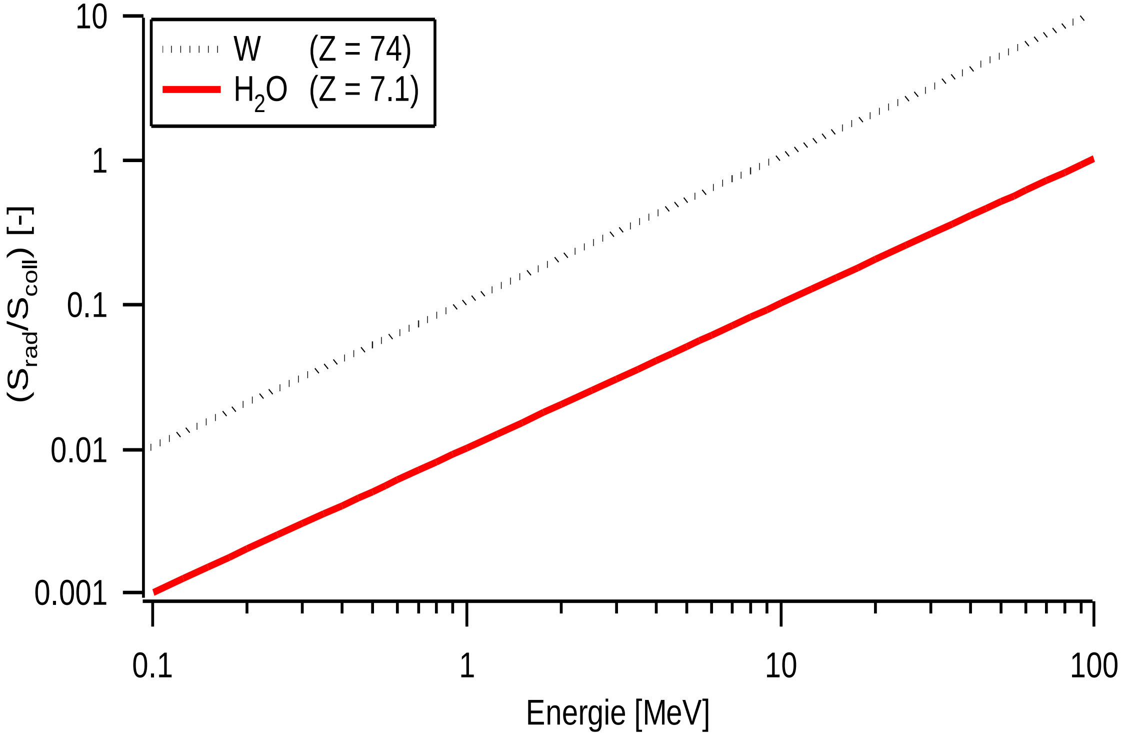



$$\frac{S_{rad}}{S_{coll}} \cong \frac{E\left[\mathrm{MeV}\right]}{700} Z$$

- 1 MeV electron in water losses about 1% of its energy by radiative interaction
- At 100 MeV, radiative braking becomes dominant over collision process

# Radiative vs. Collision stopping

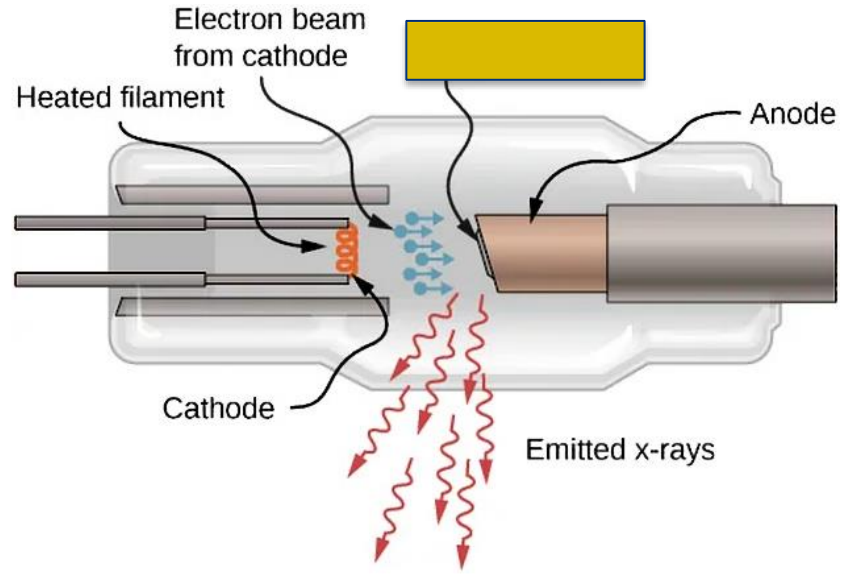
## Dependace on material (Z)




- The likelihood of a radiative process increases with the number of protons (Z)

# X-ray tube

**Q6:** Which elements would you use as a conversion target (anode) in an X-ray tube?

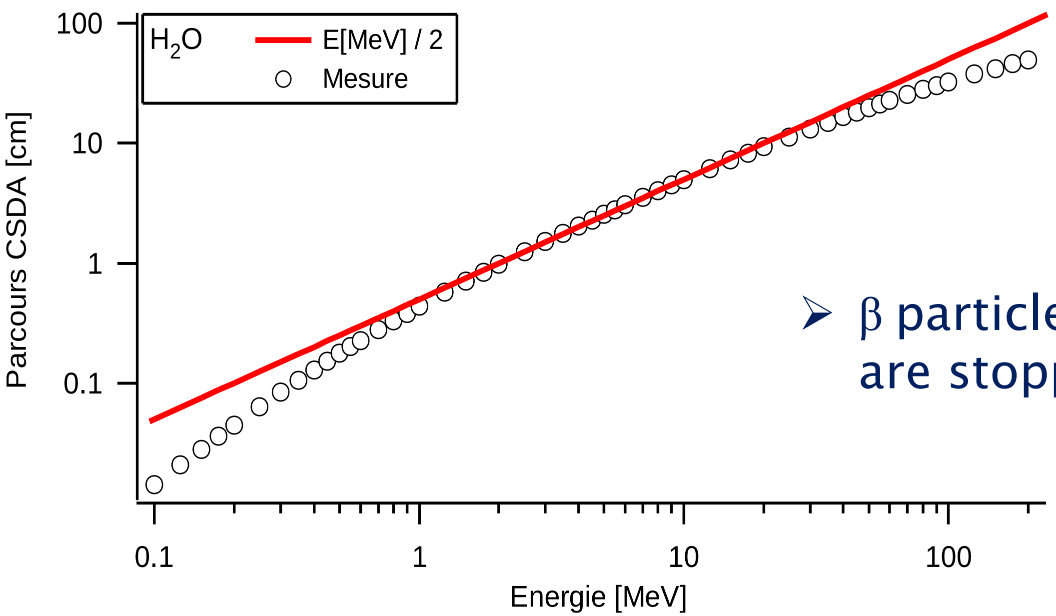


# β-sources

**Q7:** What type of shielding would you use for intense high energy β-sources ?

# Electron range in matter

- The range of the electrons in matter depends directly on the energy of the particle (the higher the energy, the larger the path)
- In the case of water, there is an empirical relationship between the range (in cm) and the energy of the monoenergetic electron beam (in MeV):

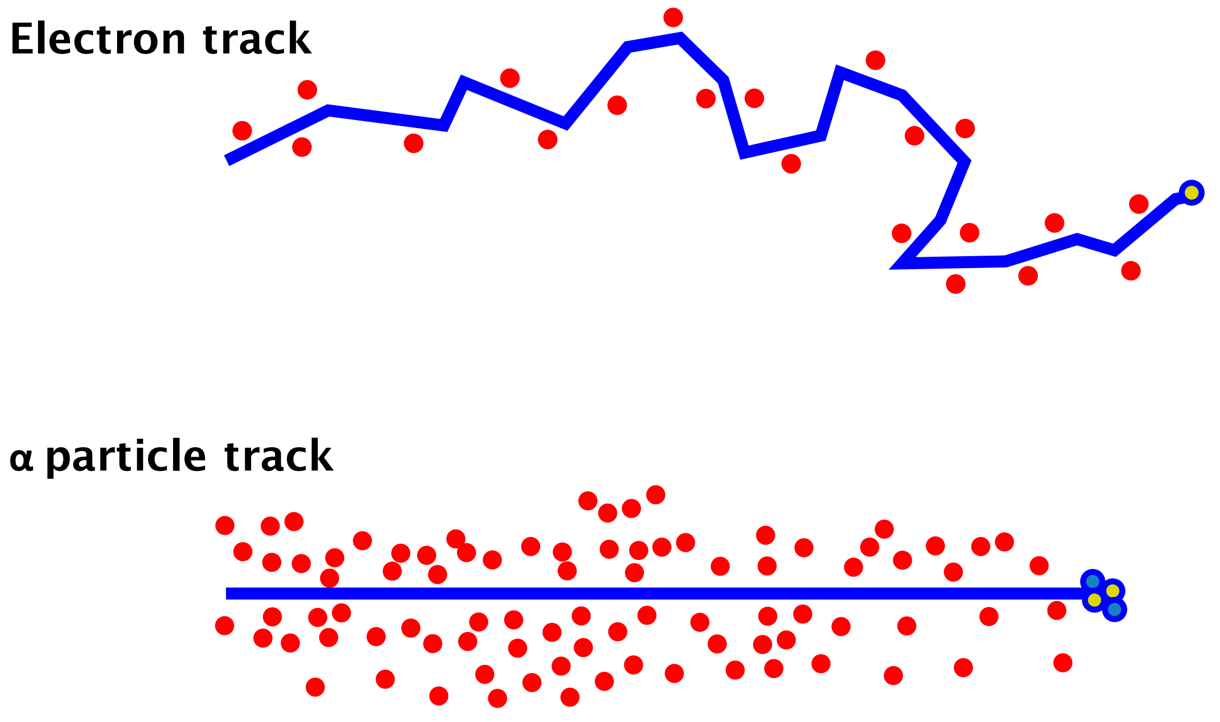



$$R_e\left[cm\right] \cong \frac{E\left[MeV\right]}{2}$$

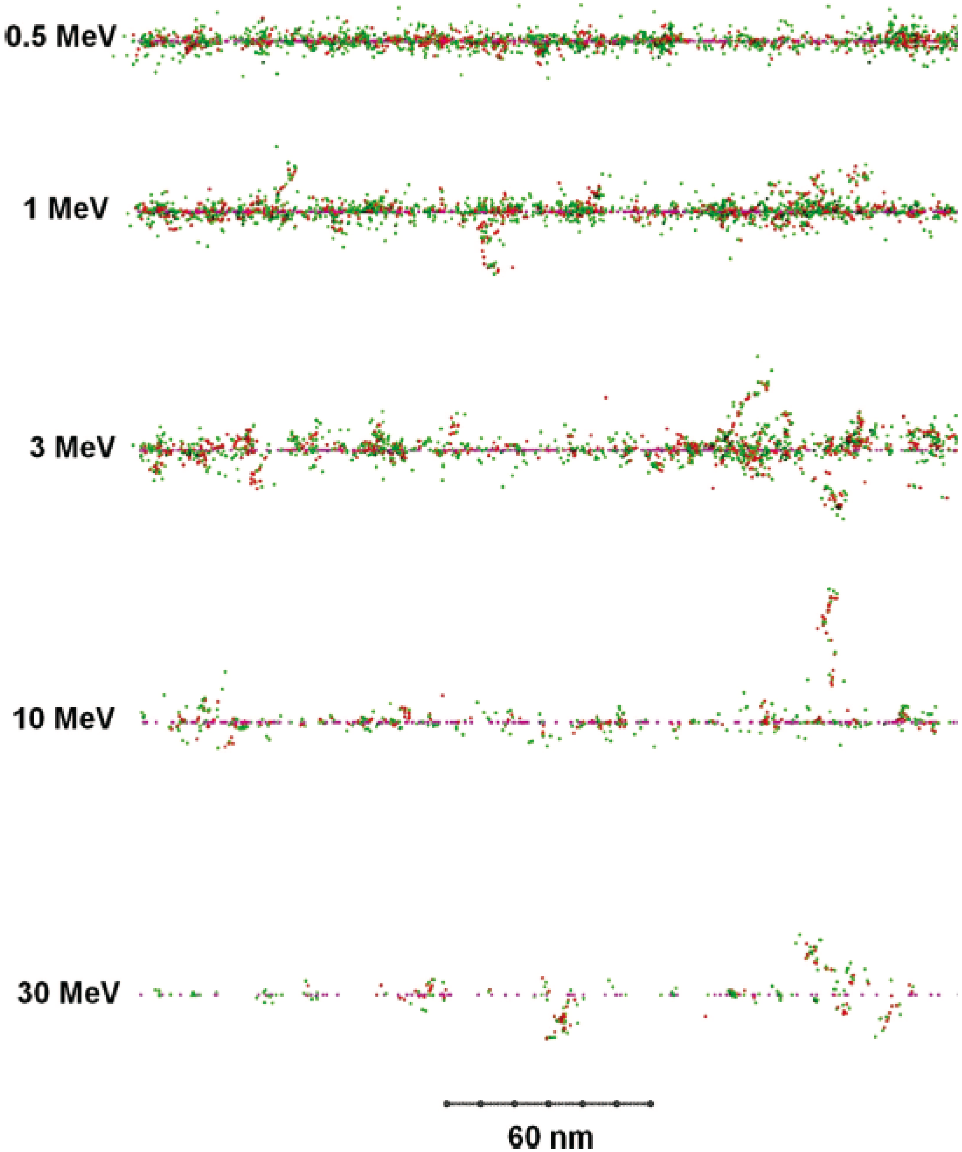
- β particles with max energy of 2 MeV are stopped by 1 cm of plexiglas

# Heavy particles

- The heavy charged particles (eg protons or α particles) interact with the material essentially by the Coulomb force. They are slowed down by collisions and not by radiative loss as for the electrons.



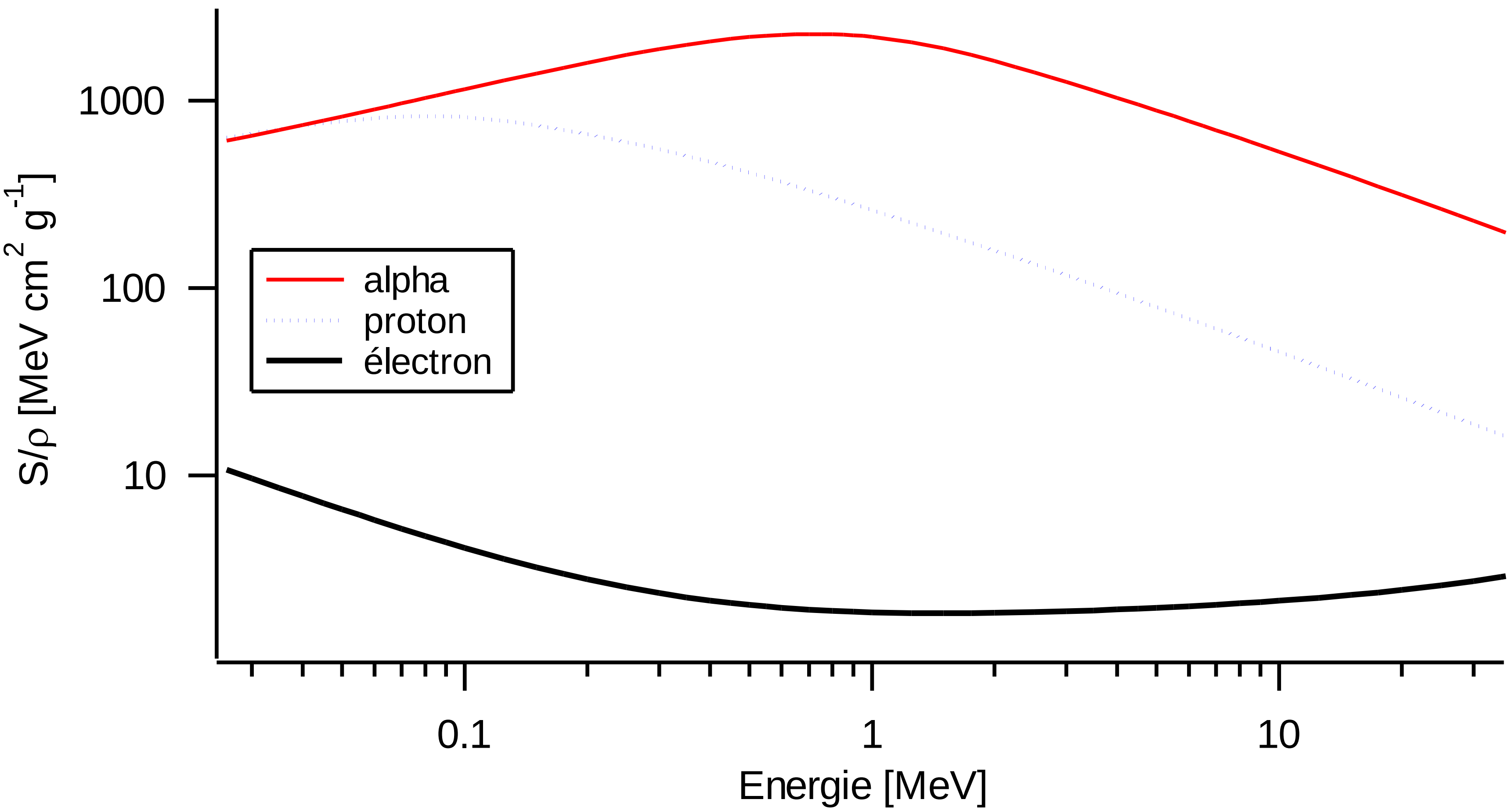
# Alpha tracks




**ICRU 86**

Figure 2.5. Calculated 230 nm track segments for 0.5 MeV, 1 MeV, 3 MeV, 10 MeV, and 30 MeV alpha particles in water. Red points represent ionizations, and green points represent excitations.

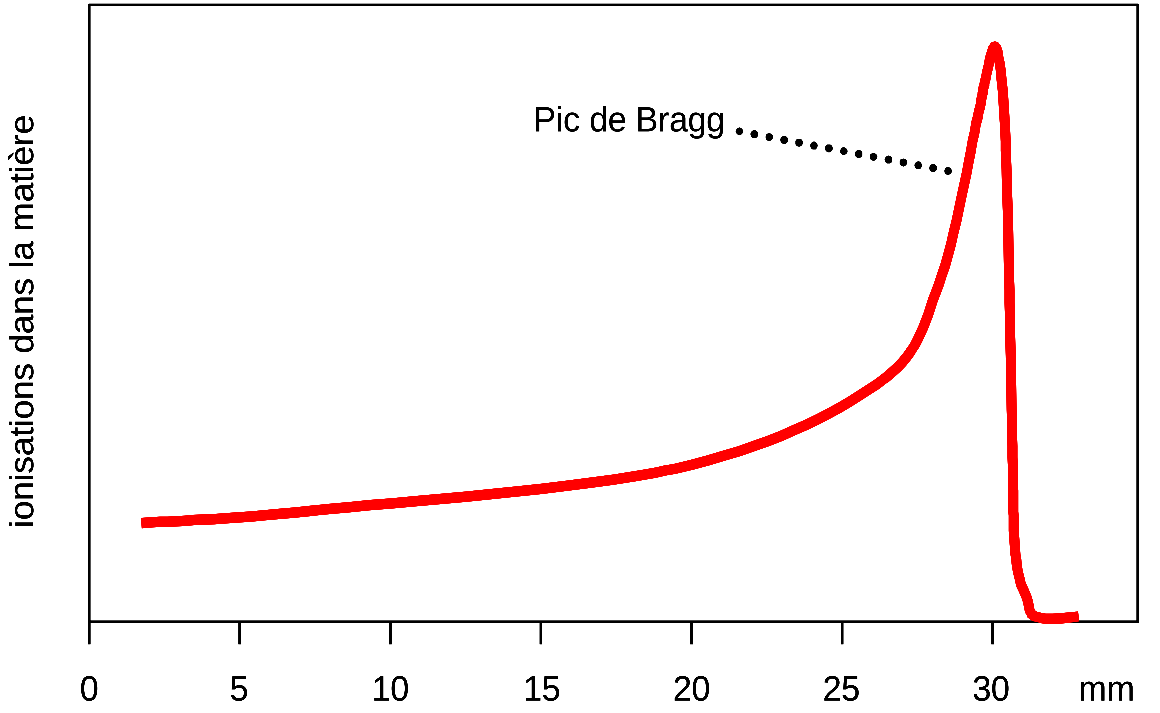
# Stopping power of heavy particles




➢ Stopping power increases with ion mass and decreases with ion energy

# The Bragg peak

➢ The Bragg peak is a direct consequence of increased stopping power of heavy particles near the end of their trajectory

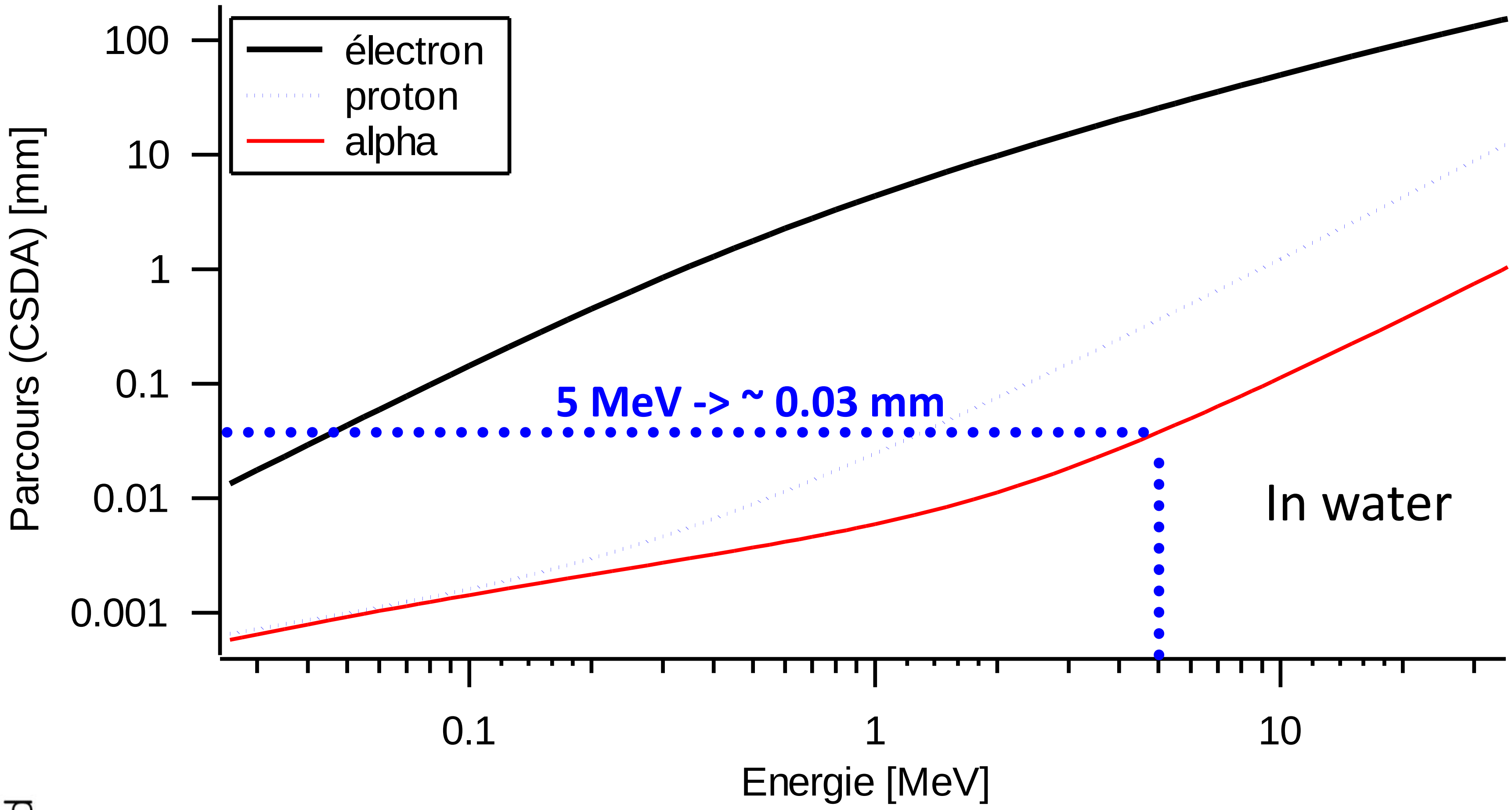



Example: 62 MeV proton beam in water

# Proton therapy

**Q8:** What is the advantage of using protons for tumor irradiation compared to  X-rays?

# Range of heavy particles in water

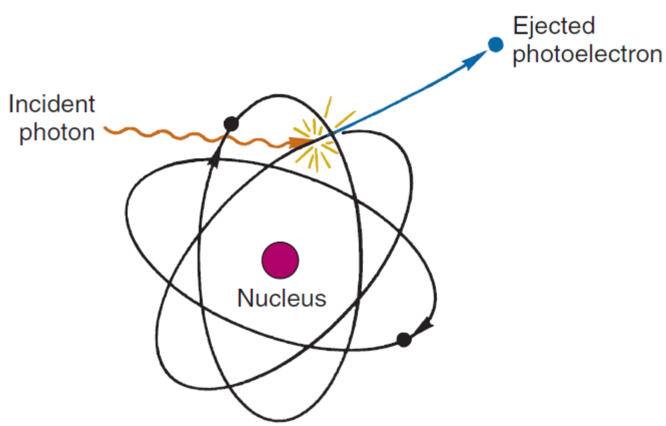


# Radon exposure

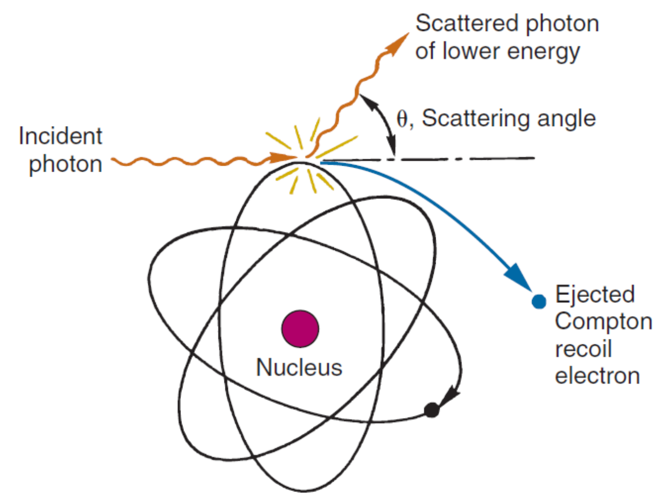
**Q9:** Which type of cancer can be caused by Rn-222 and why?

# Interaction of photons with matter

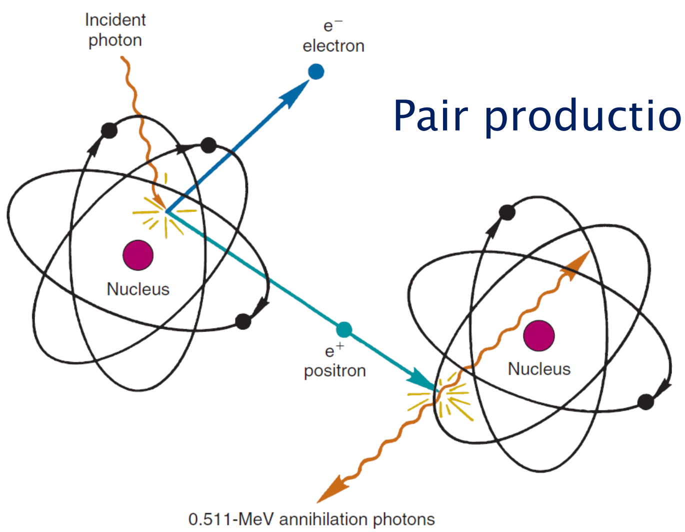
## Photoelectric effect




## Compton scattering



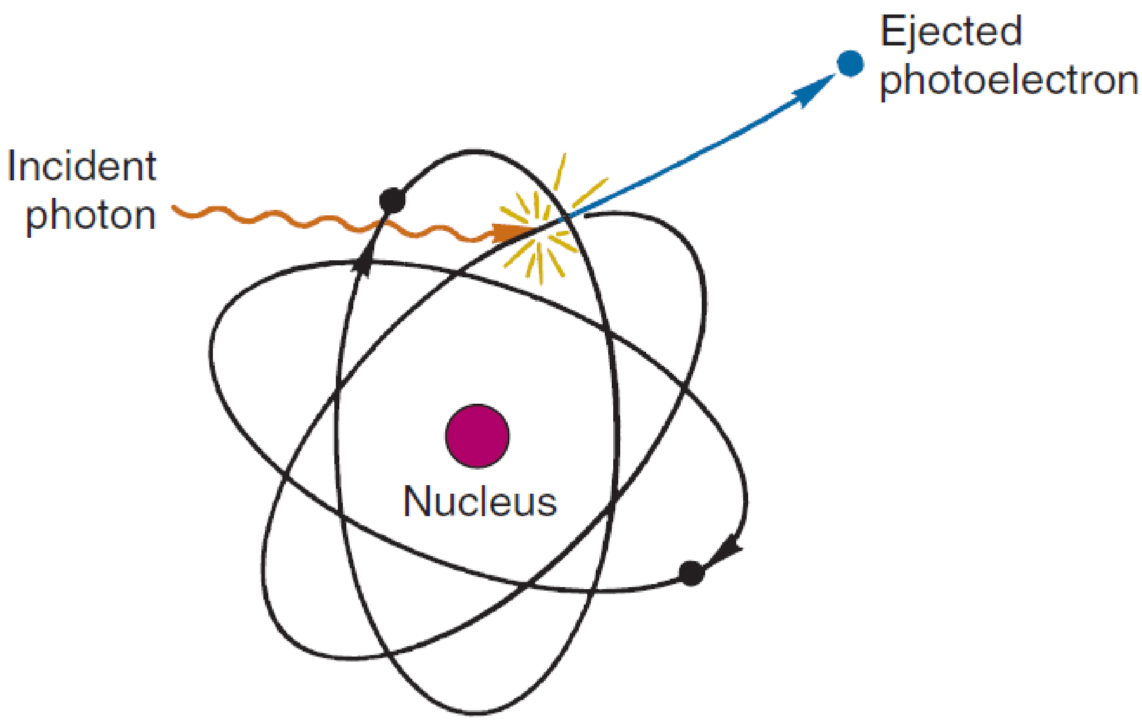

## Pair production



# Interaction of photons with matter

## Photoelectric effect

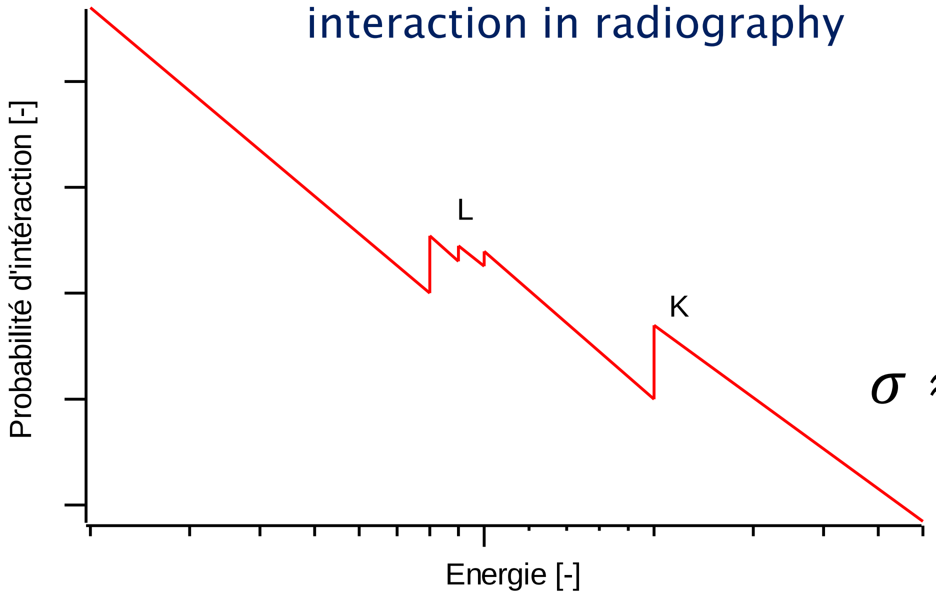
- The photoelectric effect consists of the absorption of a photon by an electron of an atom.
- The photon disappears in the interaction and gives all its energy to the electron. The atom is then ionized.



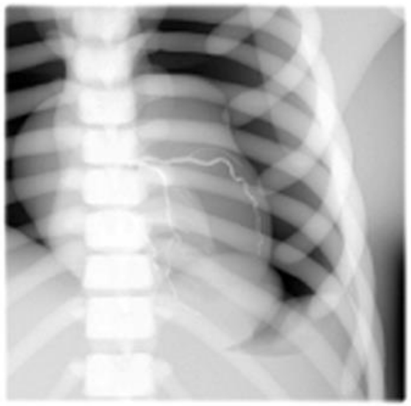
# Interaction of photons with matter

## Photoelectric effect

- The photoelectric effect is important at low photon energies
- This makes the photoelectric effect the most important photon interaction in radiography




$$\sigma \approx \frac{Z^n}{E^3}$$



- The probability of the photoelectric effect is increasing with the atomic number (Z). Typically, n is between 3 and 4.

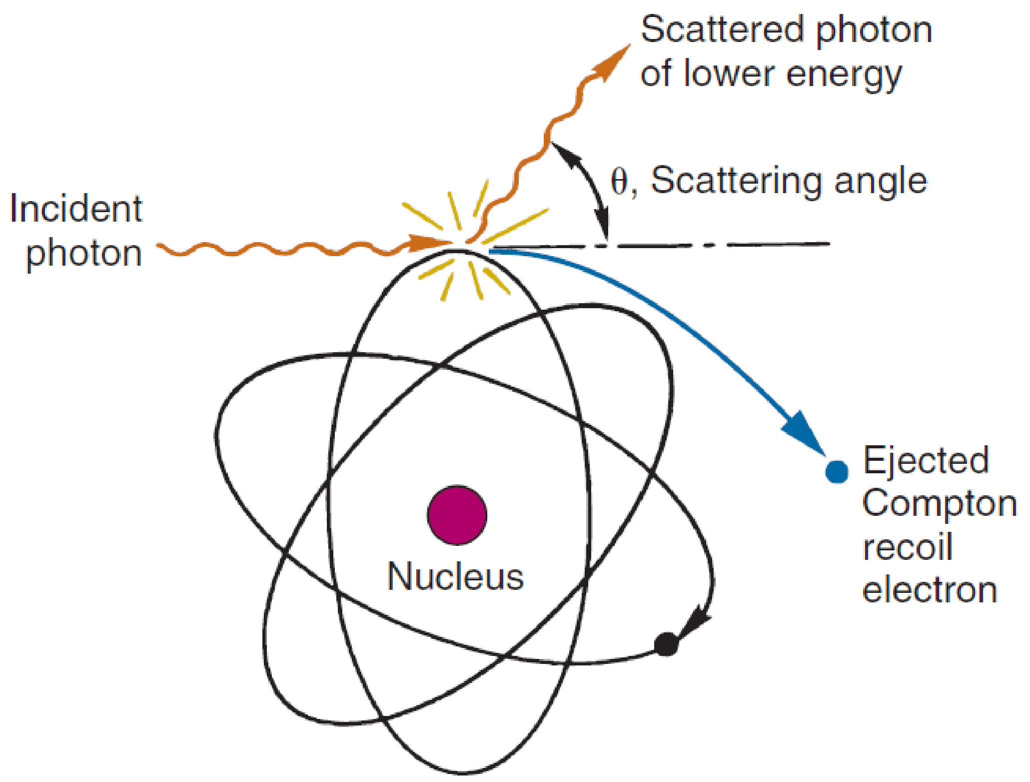
# Shielding against X-rays

**Q10:** What type of material would you use to protect from X-rays?

# Interaction of photons with matter

## Compton scattering

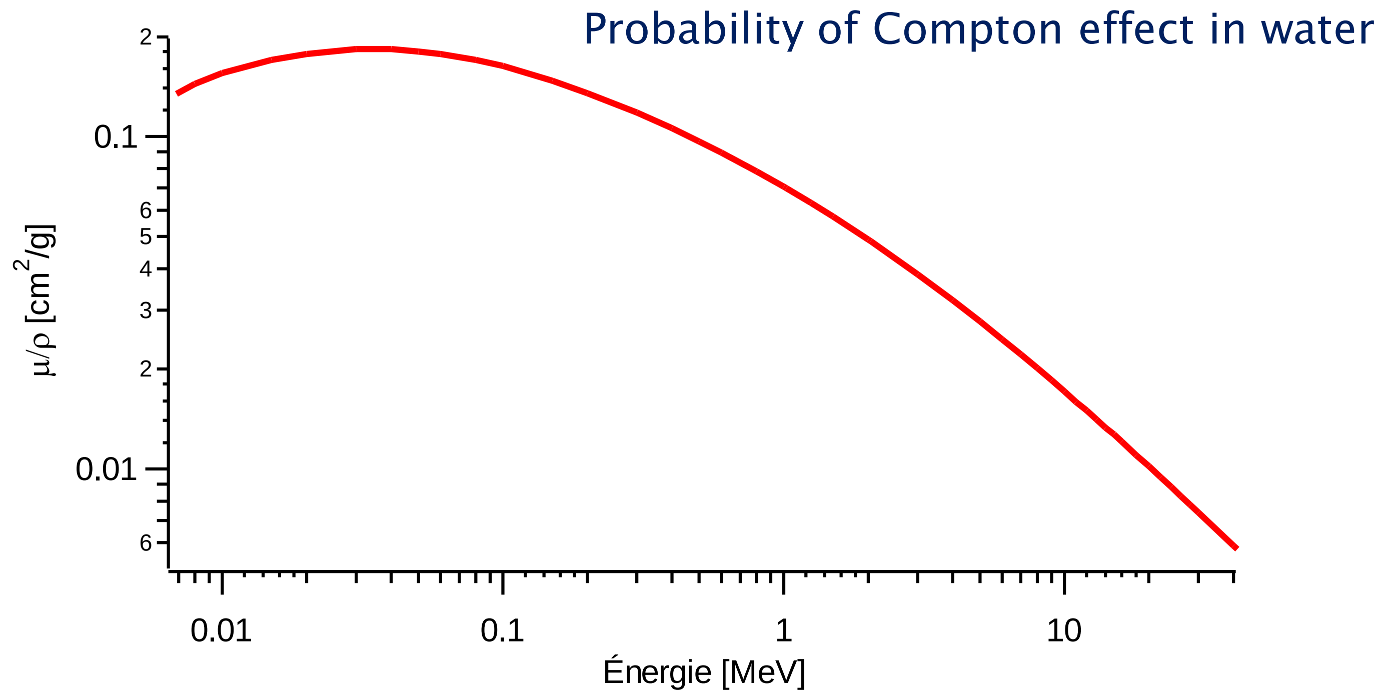
- Part of the energy of the photon is transmitted to the electron. The rest of the energy appears as a scattered photon.



# Interaction of photons with matter

## Compton effect

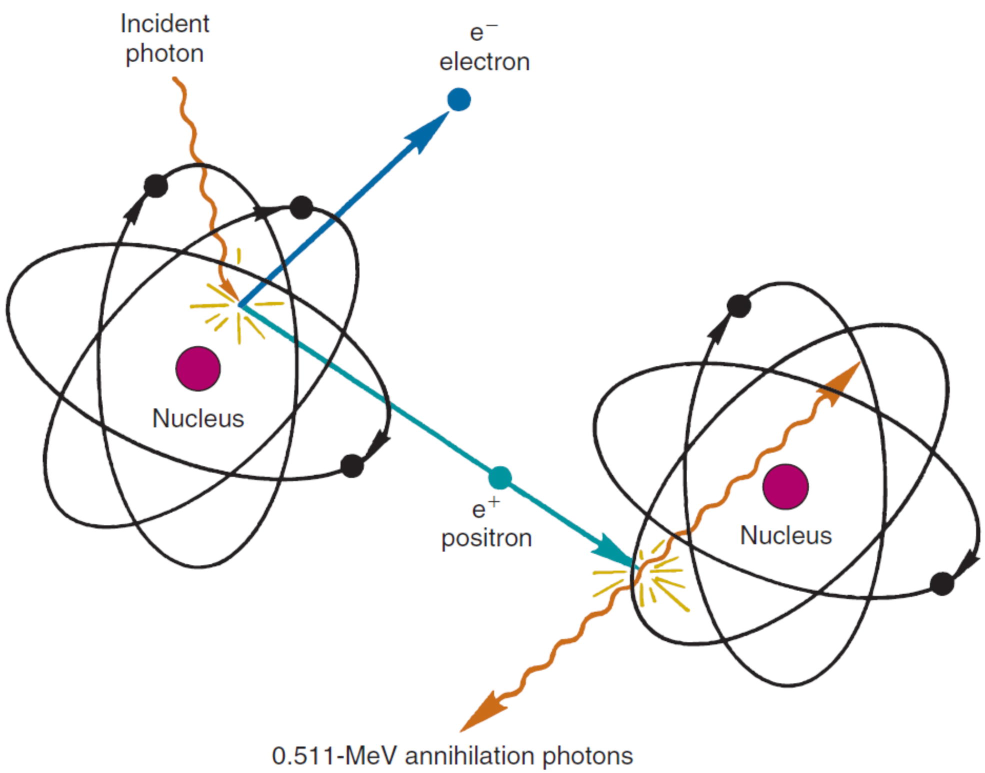
- Probability of Compton effect depends on photon energy, dominant at medium energy. But it occurs in all materials and at all energies.
- Probability of Compton effect does not depend on Z, it depends on electron density which varies by only 20% from lightest to heaviest elements.



# Interaction of photons with matter

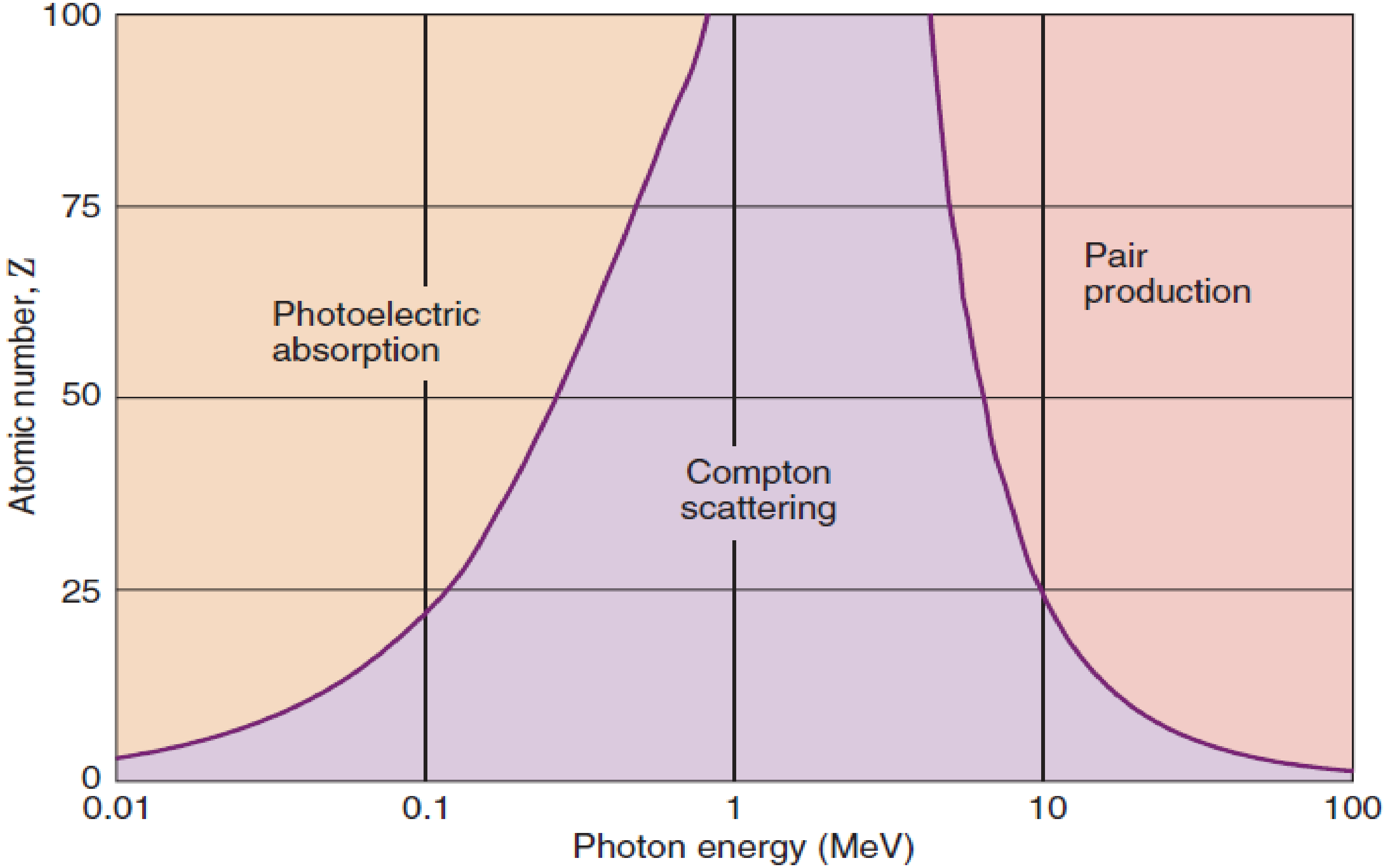
## Pair production

- High-energy photon converts into electron and positron close to atomic nuclei
- Energy converted directly into matter.
- The minimum energy required for the incident photon for a pair creation to be possible is 1022 keV (twice 511 keV).

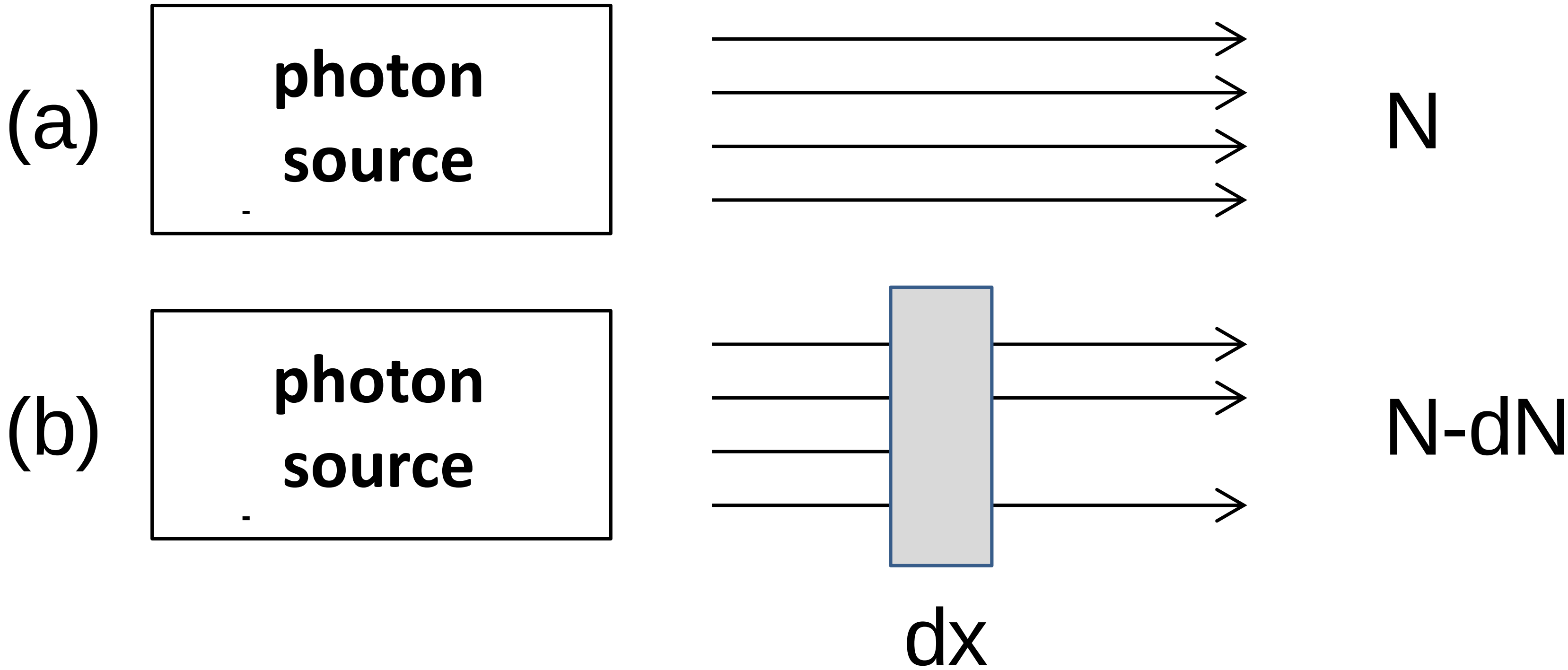


# Interaction of photons with matter

Interaction mechanism as a function of photon energy and Z of the medium:



# Photon beams attenuate, no range




Proportion interacting: **dN/N**

$$\mu = \frac{1}{dx}\frac{dN}{N} \quad \Rightarrow \quad N(x) = N_0\, e^{-\mu x}$$

# Photon attenuation: half value layer

$$N(x) = N_0 \, e^{-\mu x}$$

$$\Downarrow$$

$$HVL = \frac{\ln 2}{\mu}$$

# Summary of penetration capabilities of radiation emitted by radioactive materials