Radioactivity mechanism and interaction of radiation with matter

RBPA course **(PHYS-450)**

11.09.2024

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 the CHUV
- provides expertise in:

Medical physics – physics of radiation therapy and medical imaging

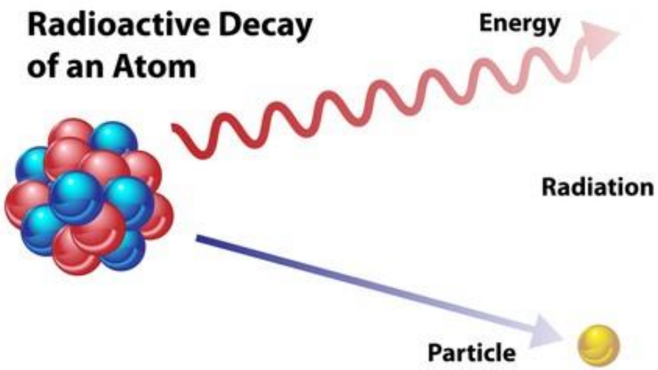
Radiation protection – protection of personnel working with ionizing radiation

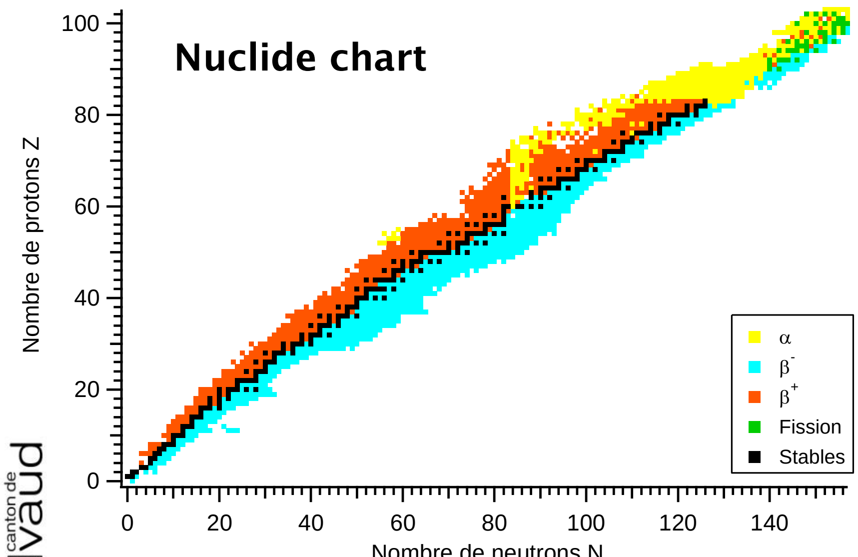
Radio-pharmaceutical chemistry – support for nuclear medicine

Radiometrology – support to everyone

Overview of Lecture 1

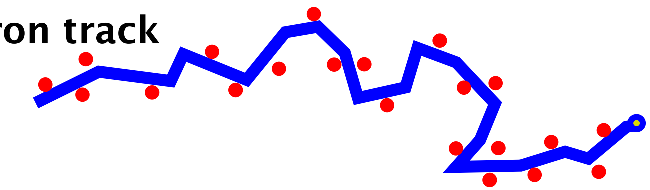
Radioactivity



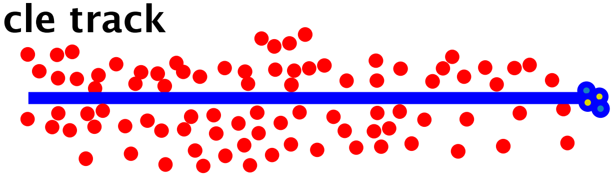


Interaction of radiation with matter

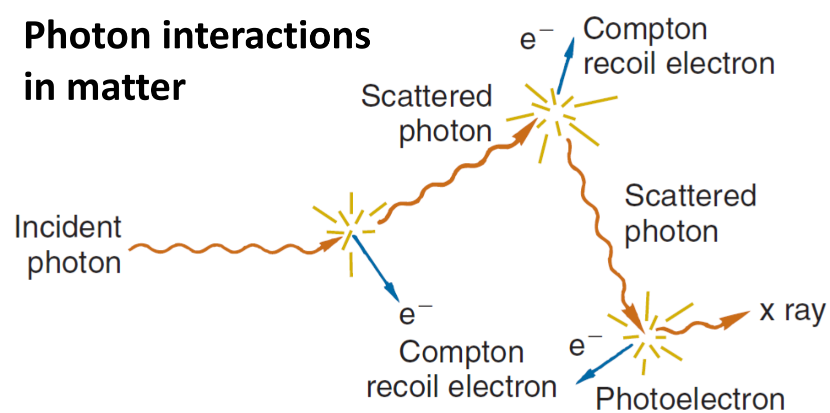
Electron track



α particle track



Photon interactions in matter



Questions to think about before we start with lecture:

- What is radiation? What is radioactivity?
- Where can we find radiation around us? Sources of radiation?
- Is all radiation dangerous for health?

Radiation

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

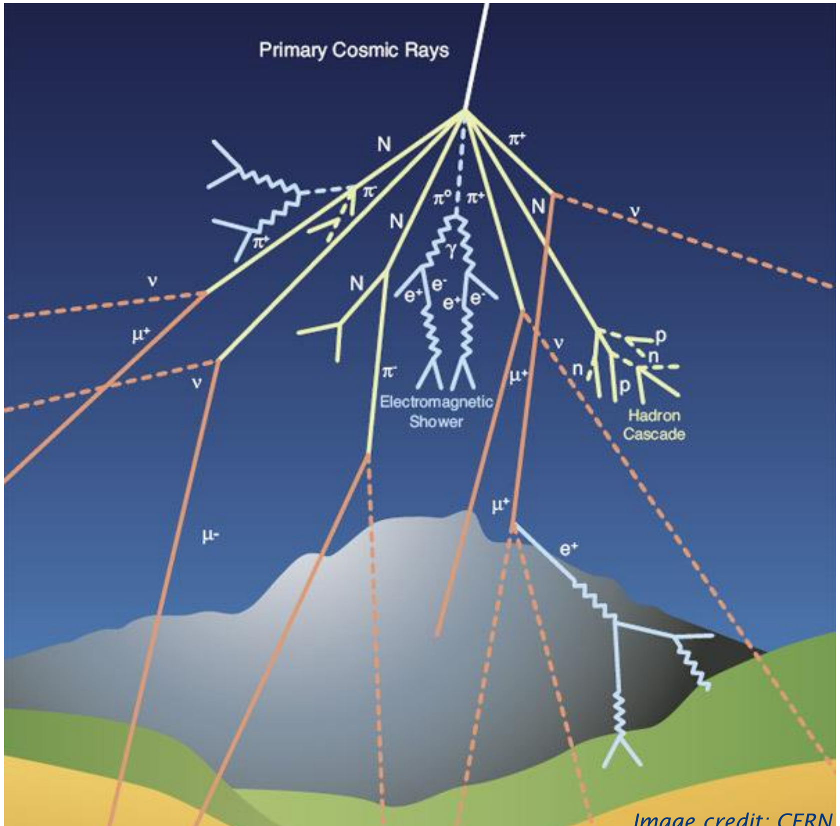
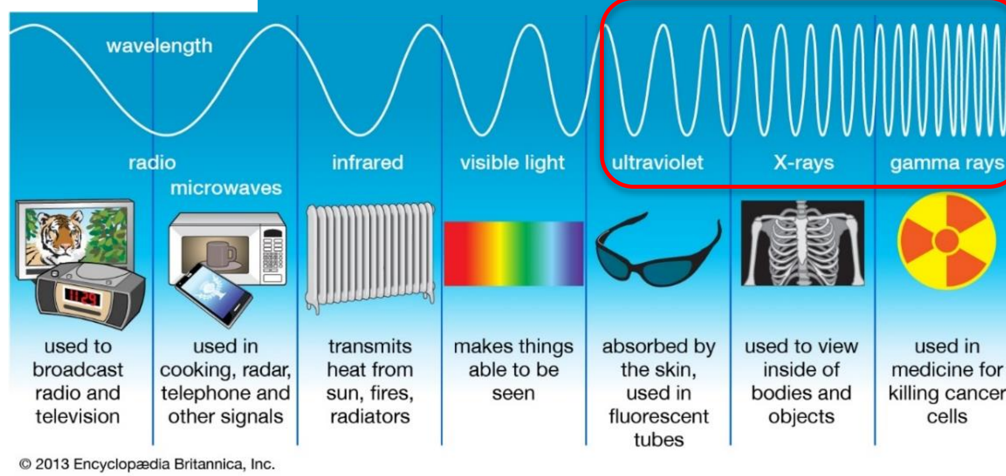


Image credit: CERN

Cosmic rays - Particles

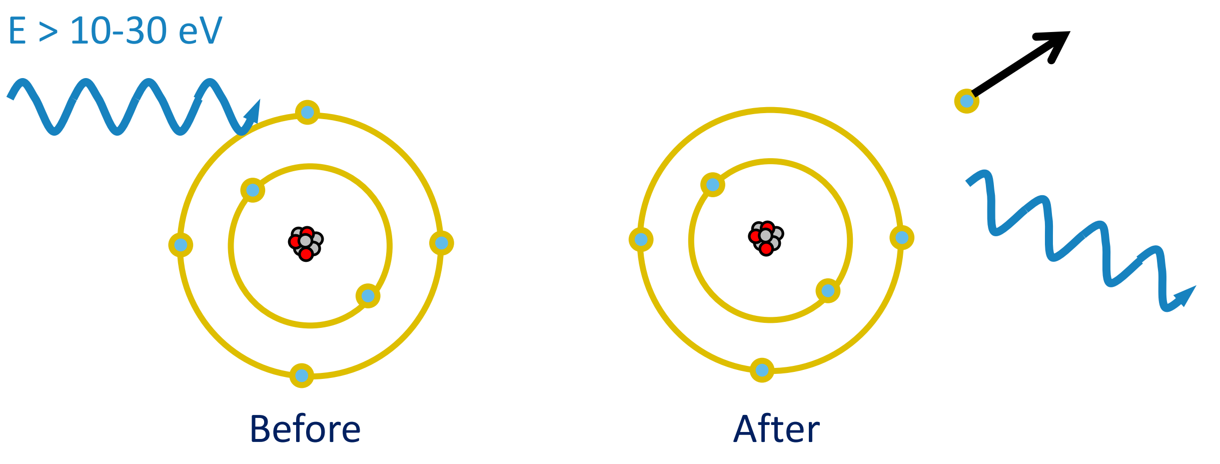
We will be interested only in ionizing radiation since it presents a health hazard

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

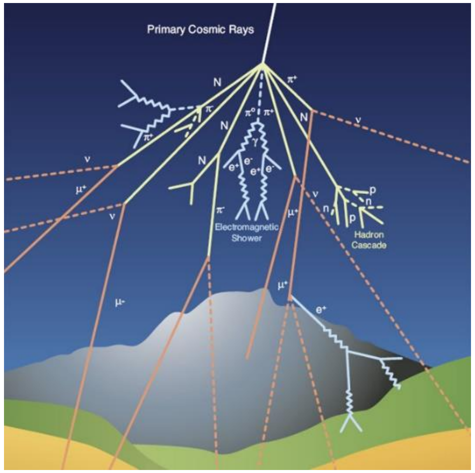


Forms of ionizing radiation:

- Particles (proton, electron, α-particles, neutron…)
- Photons (UV, X-rays, γ-rays)

Sources of ionizing radiation on Earth

1) Cosmic rays

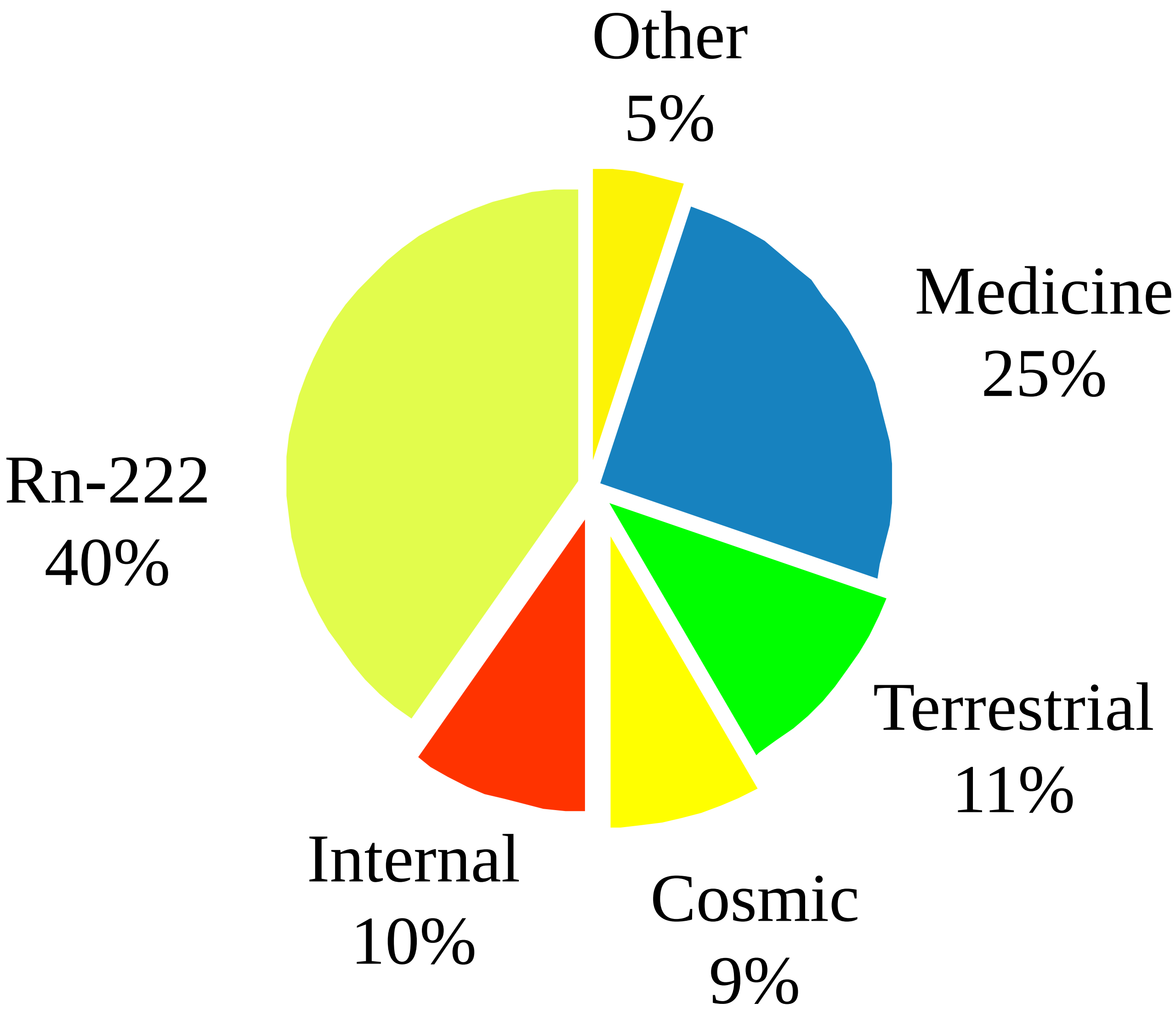


2) Naturally occurring radioactive materials

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

3) Man-made sources

Population radiation exposure in Switzerland

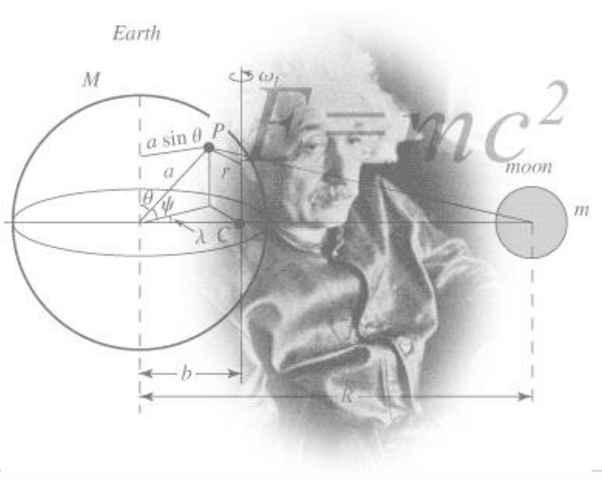


RADIOACTIVITY

Lecture objectives

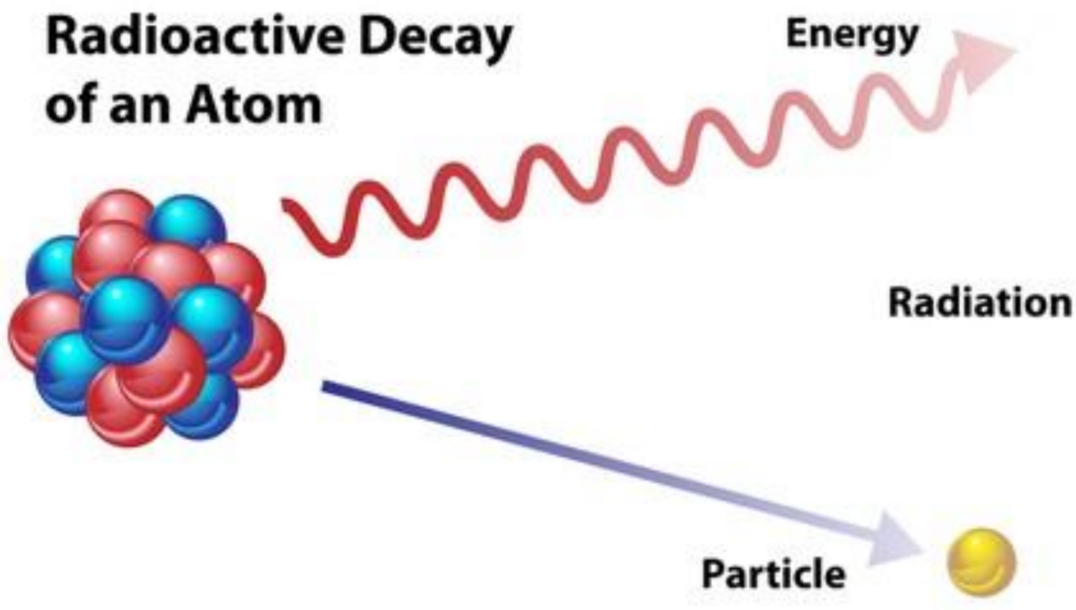
At the end of the lecture you should be able to :

- Describe different decay possibilities of radiactive nucleus
- Describe the concepts of activity, decay and half-life
- Use the radionuclide charte to determine the characteristics of a particular decay chain



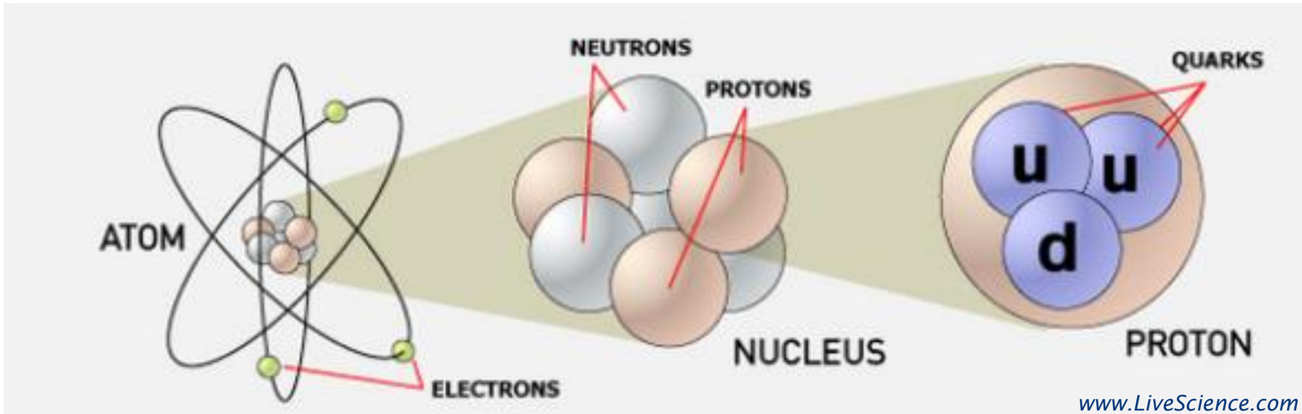
What is radioactivity?

- 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

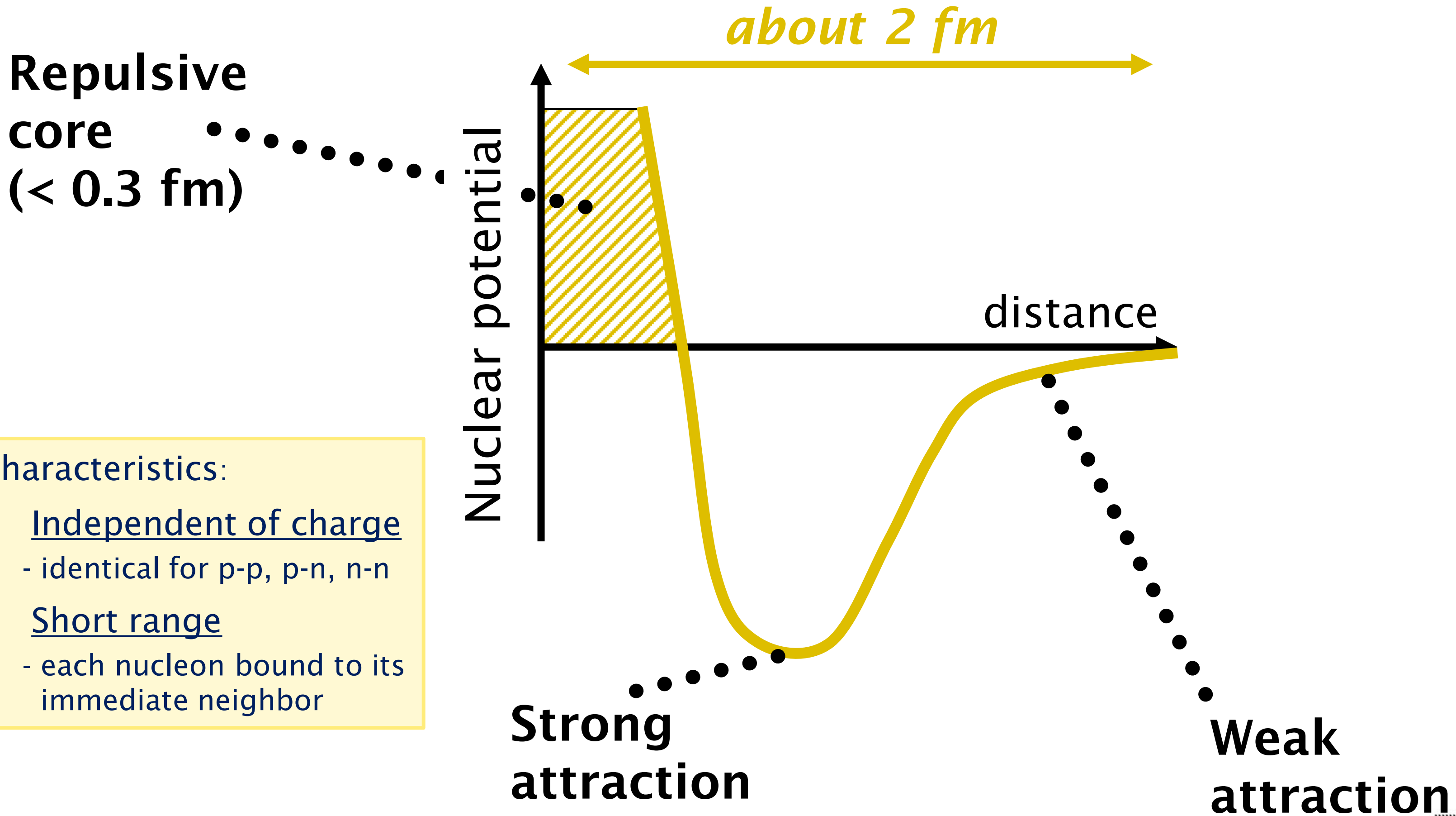
$m_p \approx m_n$

m_p = **1836** m_e

What binds nucleons together?

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

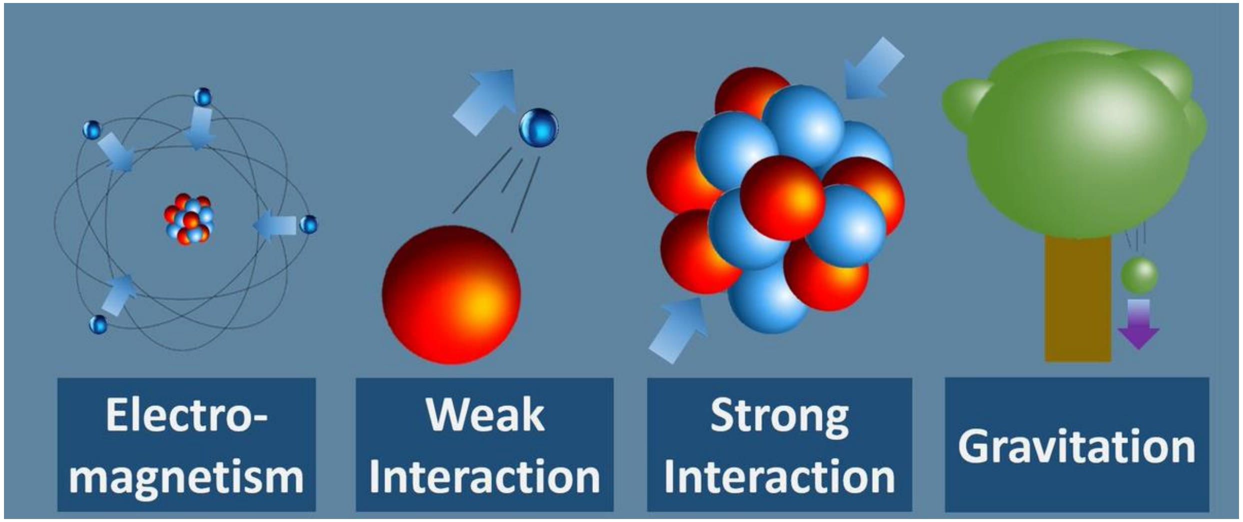
Answer: **Strong nuclear force**



Characteristics:

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

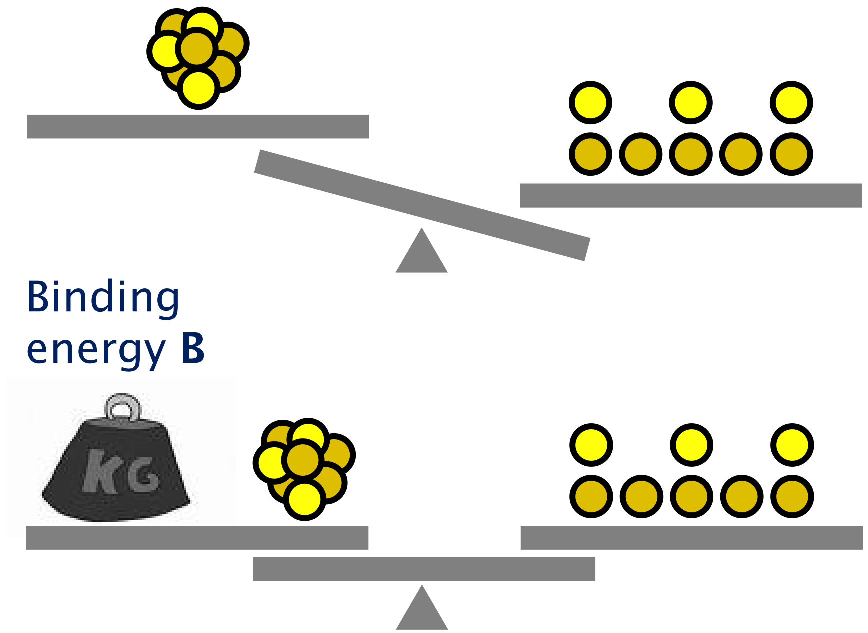
The four fundamental forces in nature



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

What binds nucleons together?

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



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

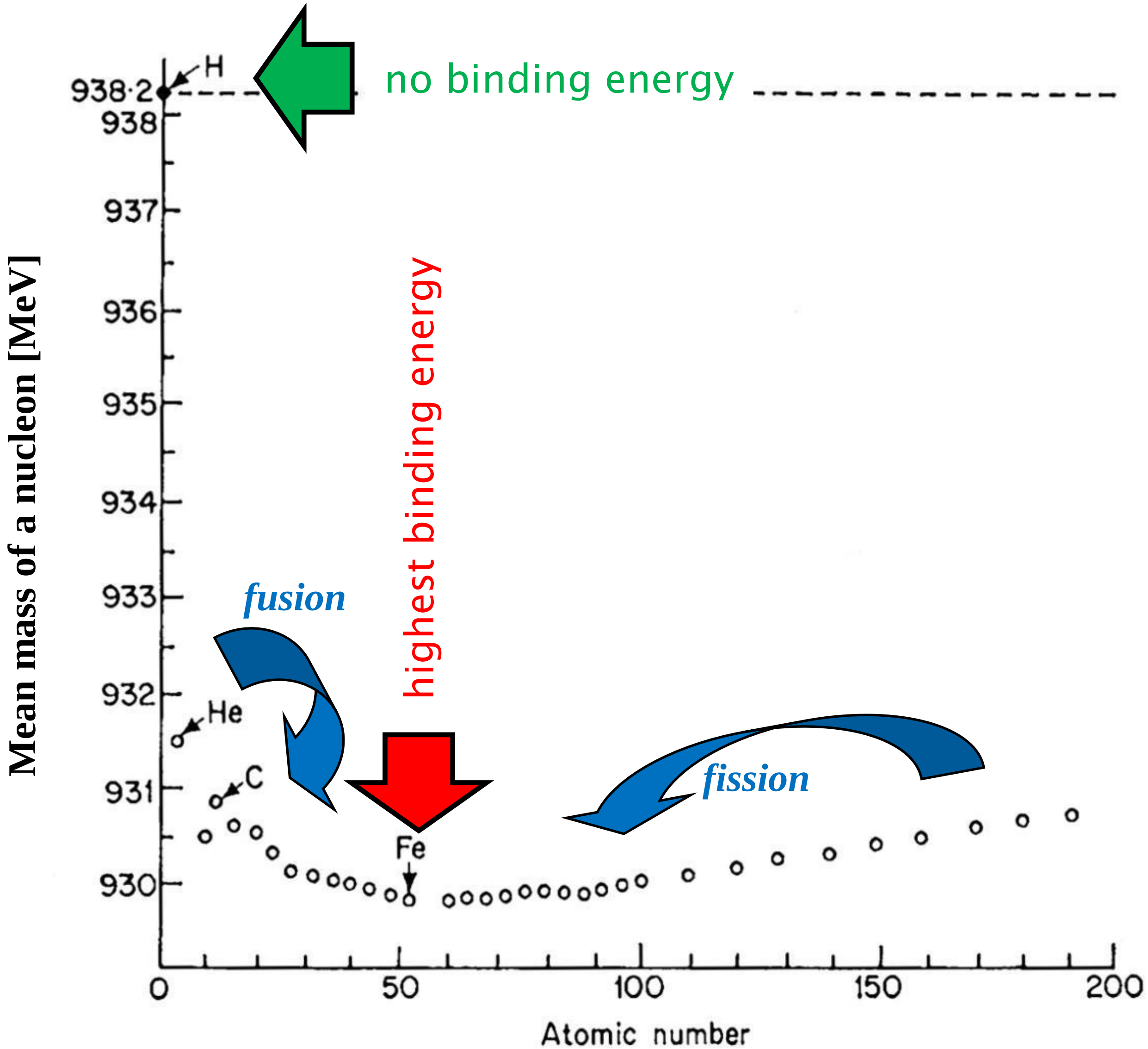
Proton energy

Neutron energy

Nucleus energy

canton de vaud

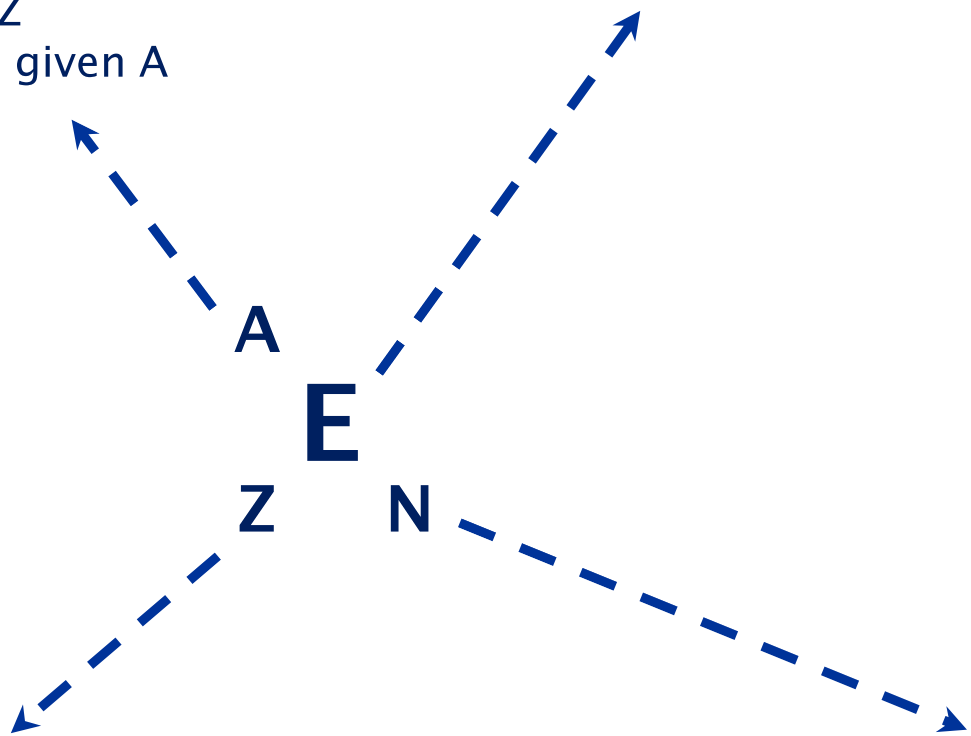
Binding energy



Nomenclature

<u>Mass number</u>
- determines the mass of a nucleus : N + Z
- different Z for a given A = isobares

<u>Element</u>
- characterised by Z



<u>Atomic number</u>
- number of protons or electrons
- chemical characteristics of the element

<u>Amount of neutrons</u>
- different N for a given Z = isotopes

Nomenclature

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

- Examples of isotops (same element, different A)

$$^{12}_{6}C_{6} \equiv {}^{12}C \equiv C-12$$

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

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

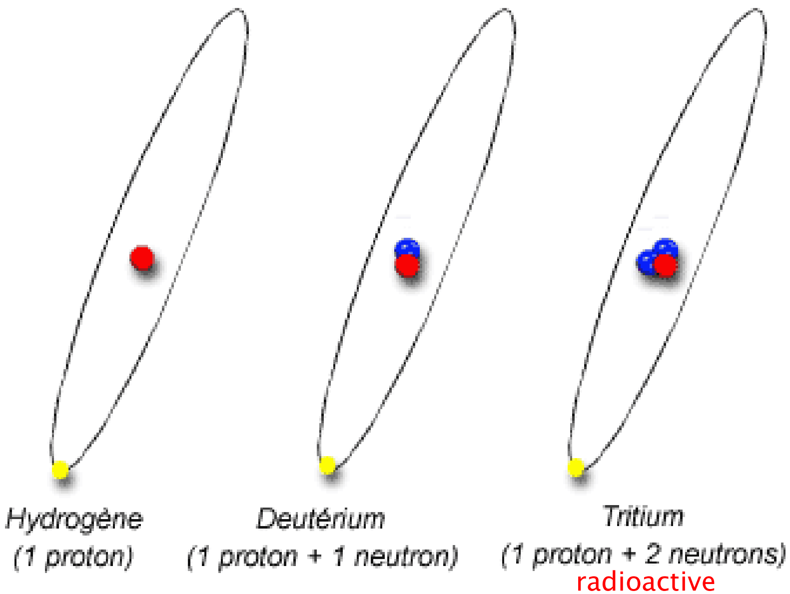
isotopes of carbon

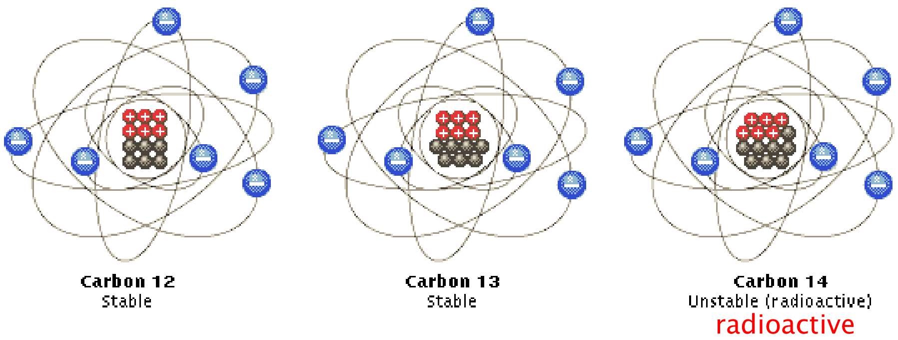
Stable and unstable nuclei

- 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





- 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

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

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

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

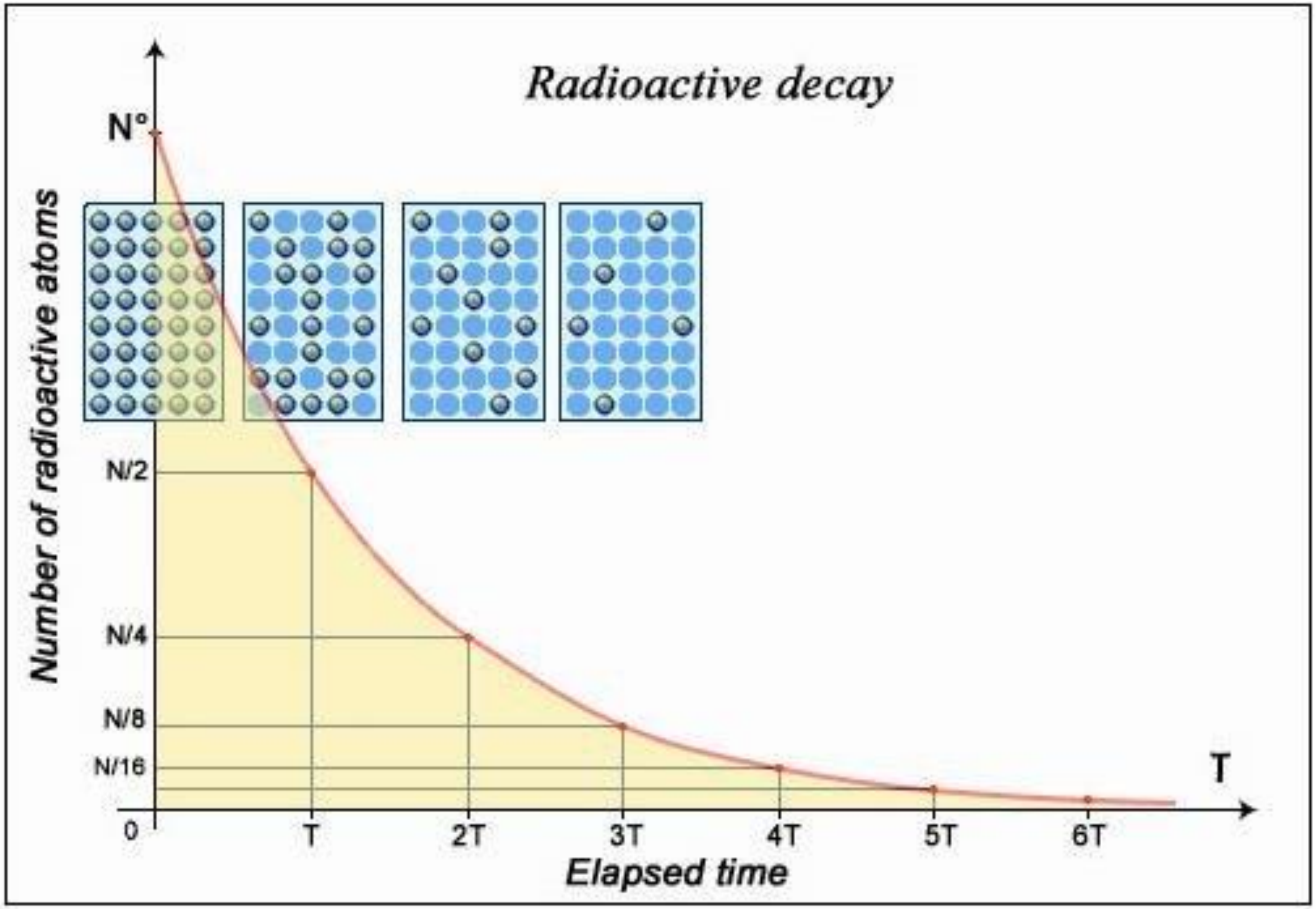
Activity A(t)

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

Q1: If you plan to inject an activity of 800 MBq of Tc-99 at 10 am, what activity should you prepare at 8 am?

$T_{1/2}$ (Tc-99) = 6 hours

Time dynamic of radioactive decay



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.

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

Half life $T_{1/2}$

Q2: How many parent radioisotopes will remain after $t = 2T_{1/2}$?

1. 50%
2. 0%
3. 25%
4. 12.5%

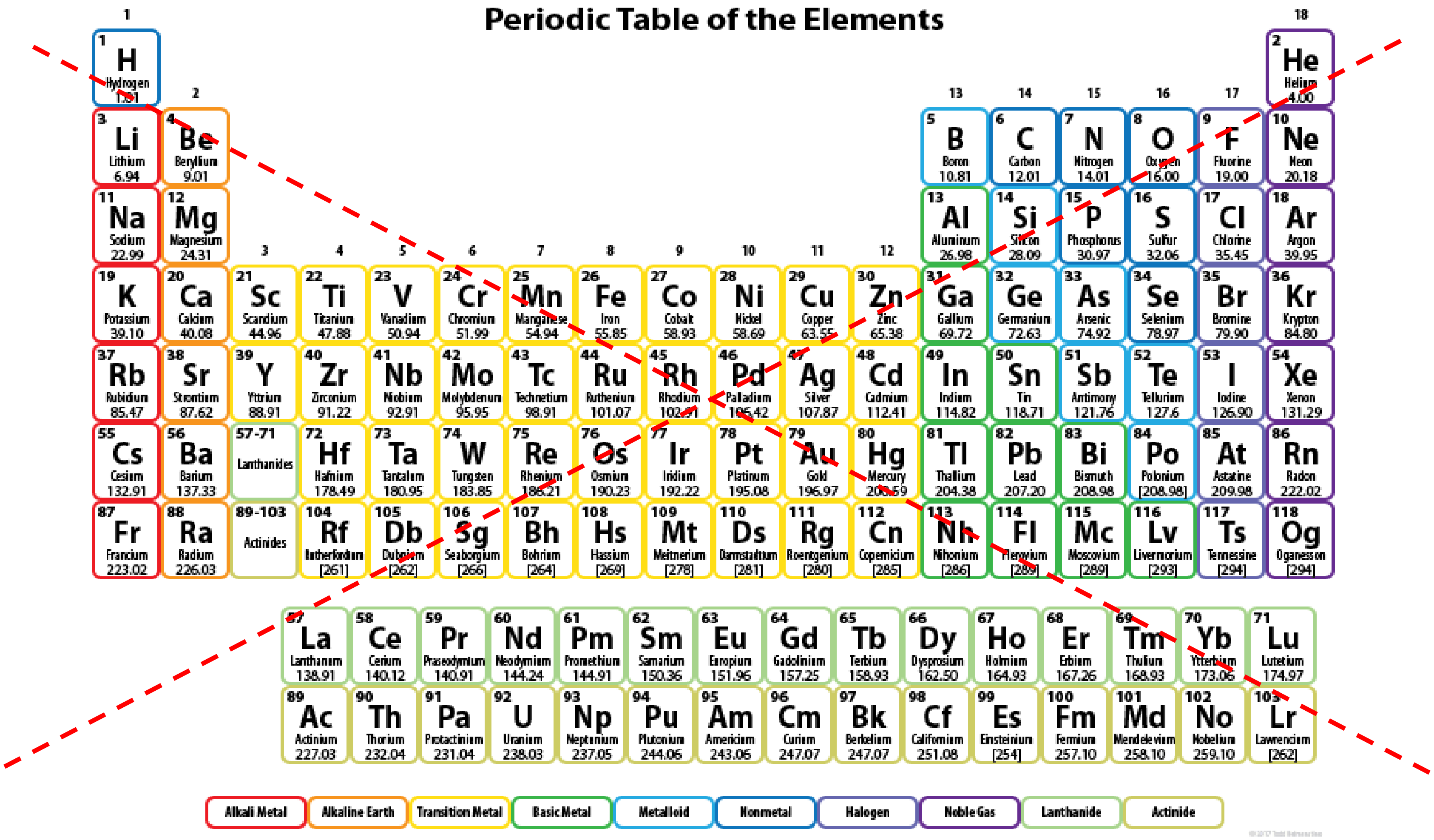
Q2: What is approximately the reduction factor od N after $t = 10T_{1/2}$?

1. 10
2. 20
3. 1000
4. 10000

Half life $T_{1/2}$

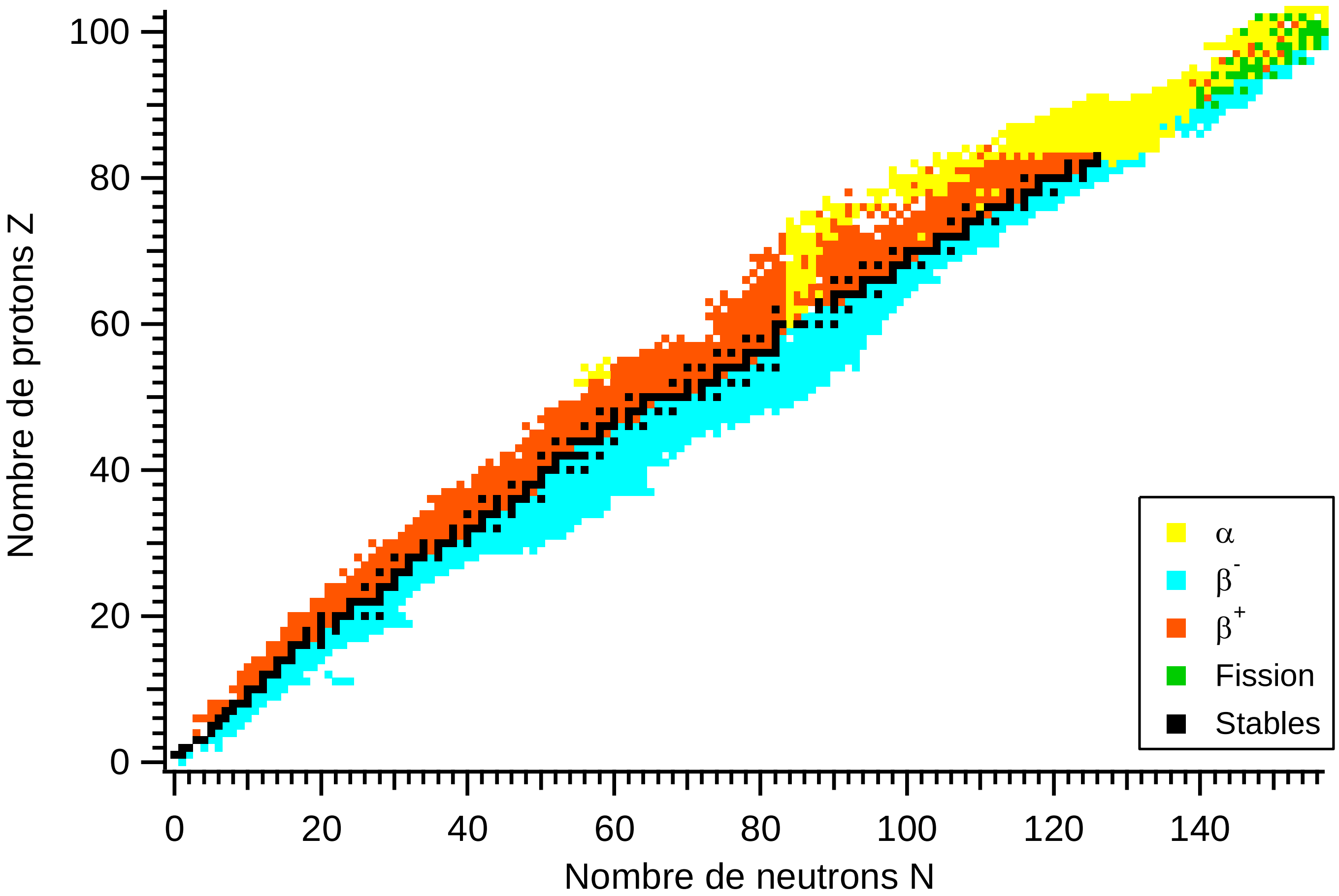
Q3: Find relationship between $T_{1/2}$ and λ (half-life and decay probability).

Where to find look for information?



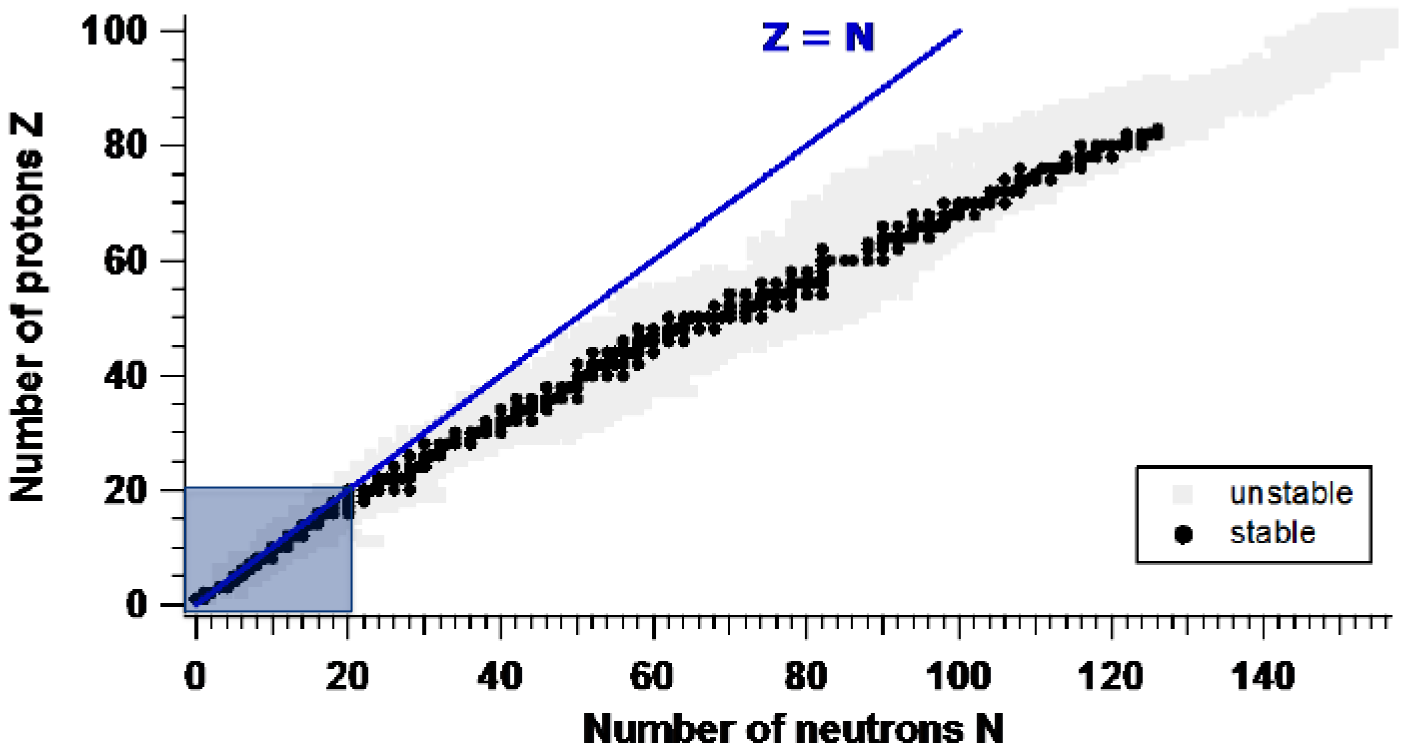
Where to find look for information?

Nuclide chart

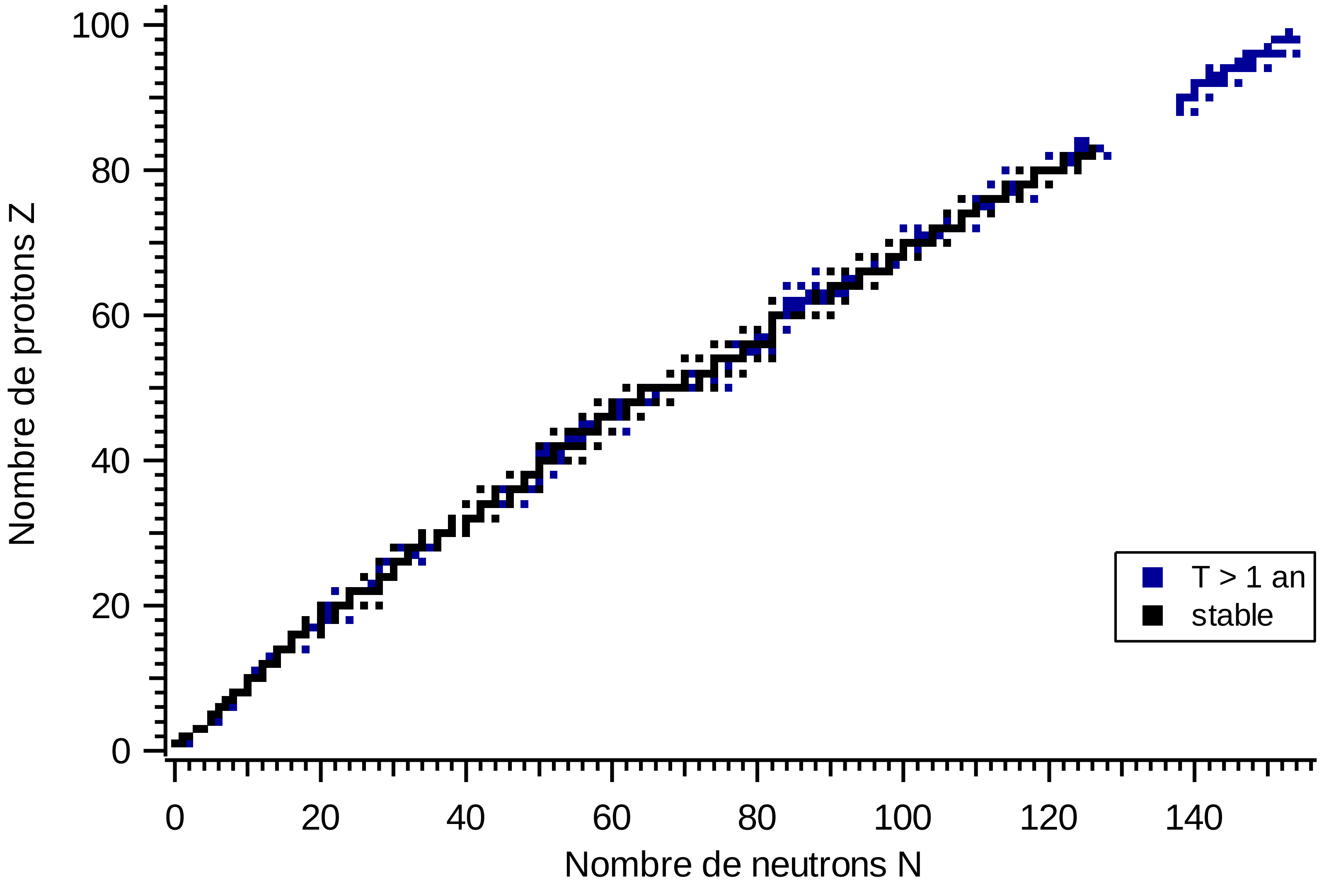


Stable nuclei

Nuclide chart

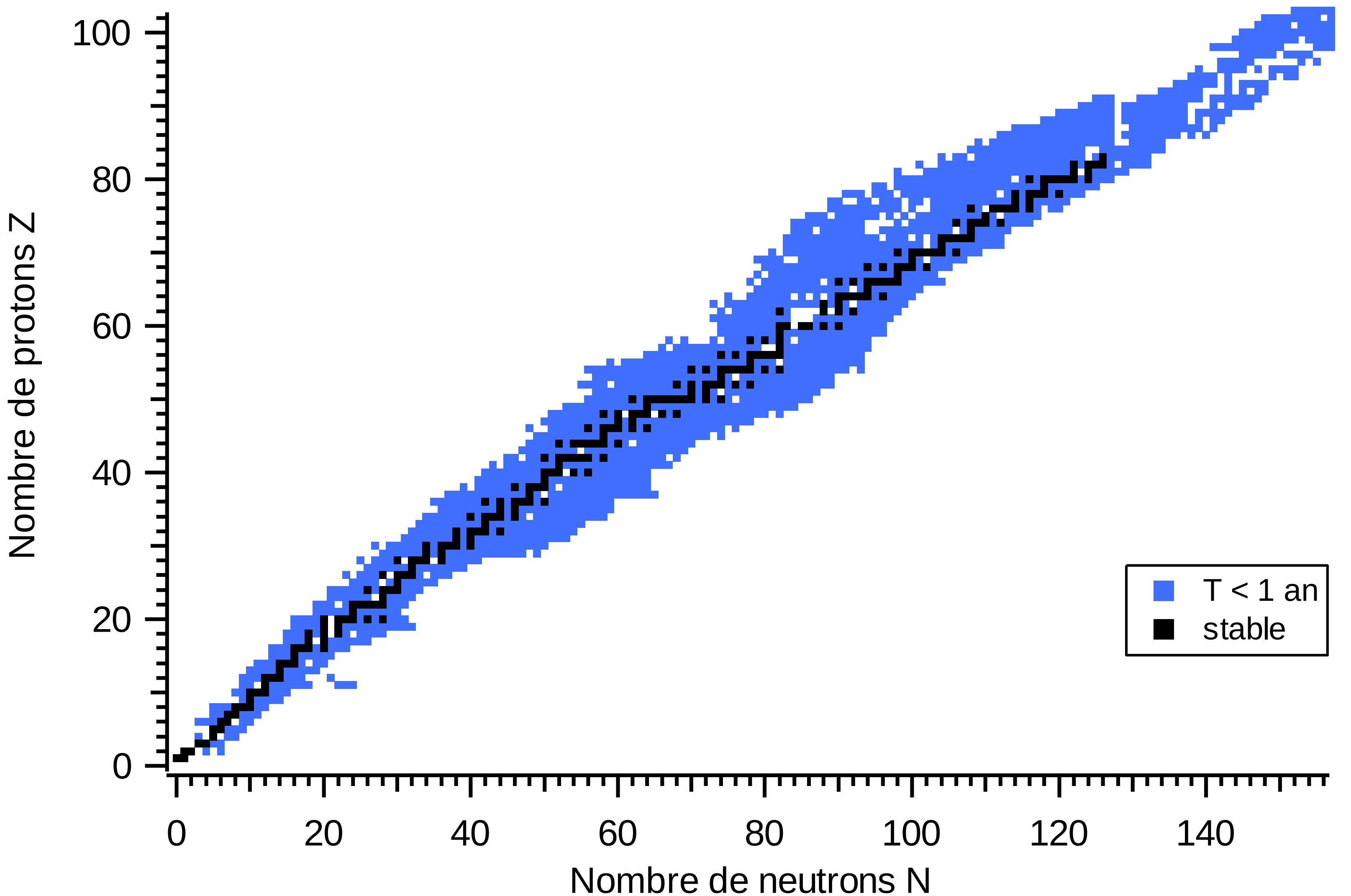


$T_{1/2}$ > 1 year



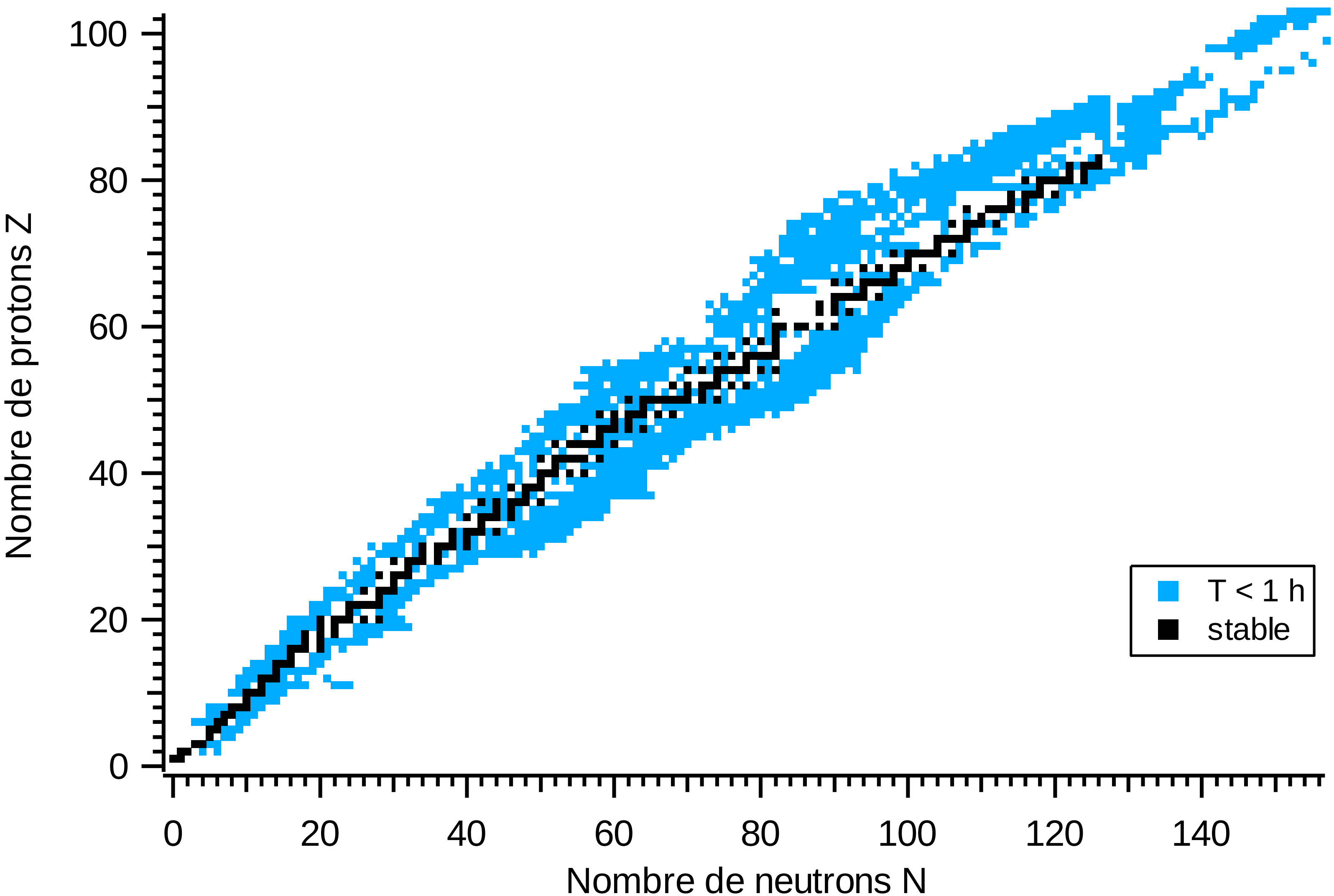
100
80
60
40
20
0
Nombre de protons Z
0
20
40
60
80
100
120
140
Nombre de neutrons N
T > 1 an
stable

$T_{1/2}$ < 1 year

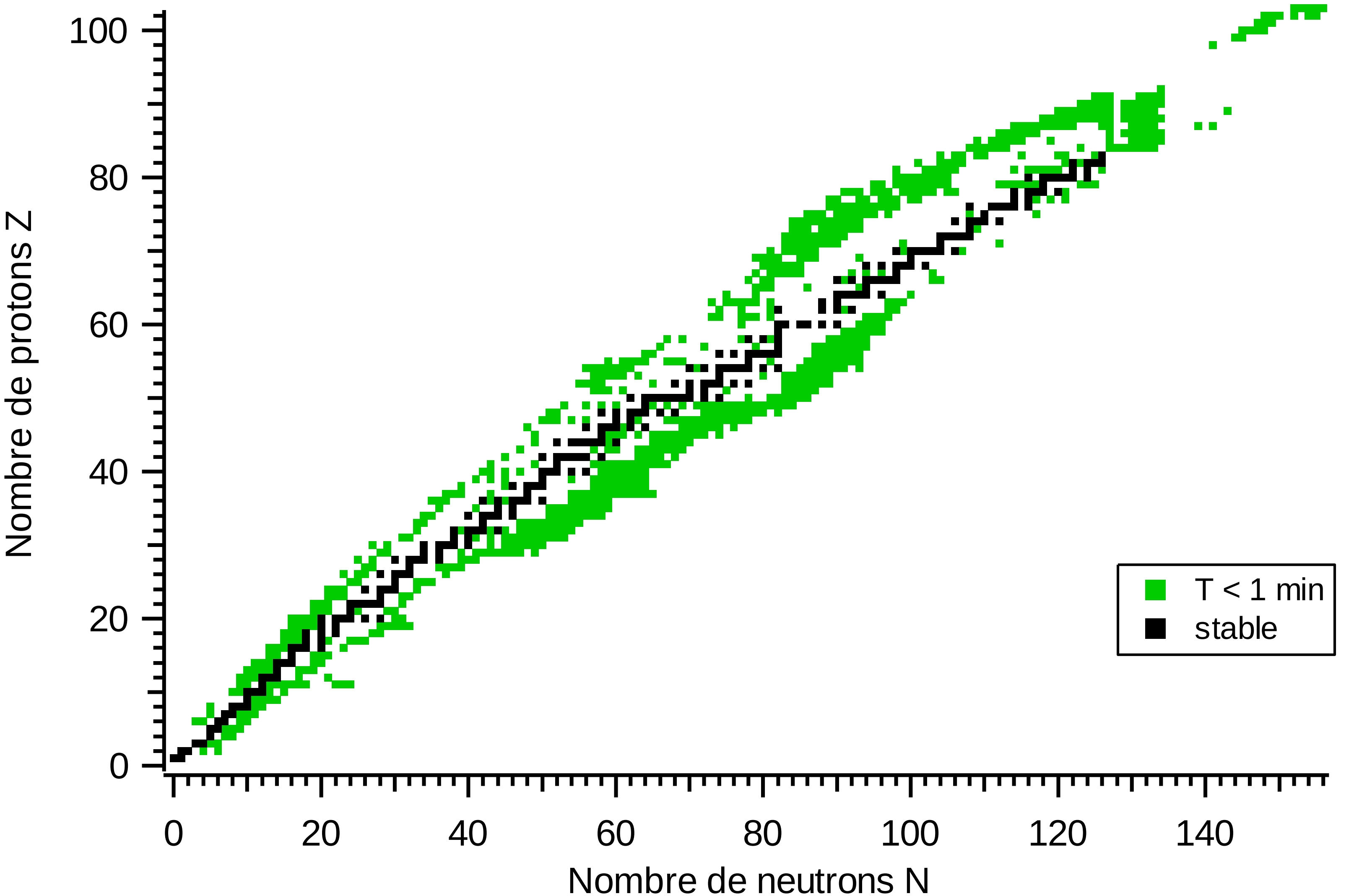


100
80
60
40
20
0
Nombre de protons Z
0
20
40
60
80
100
120
140
Nombre de neutrons N
T < 1 an
stable

$T_{1/2} < 1$ h

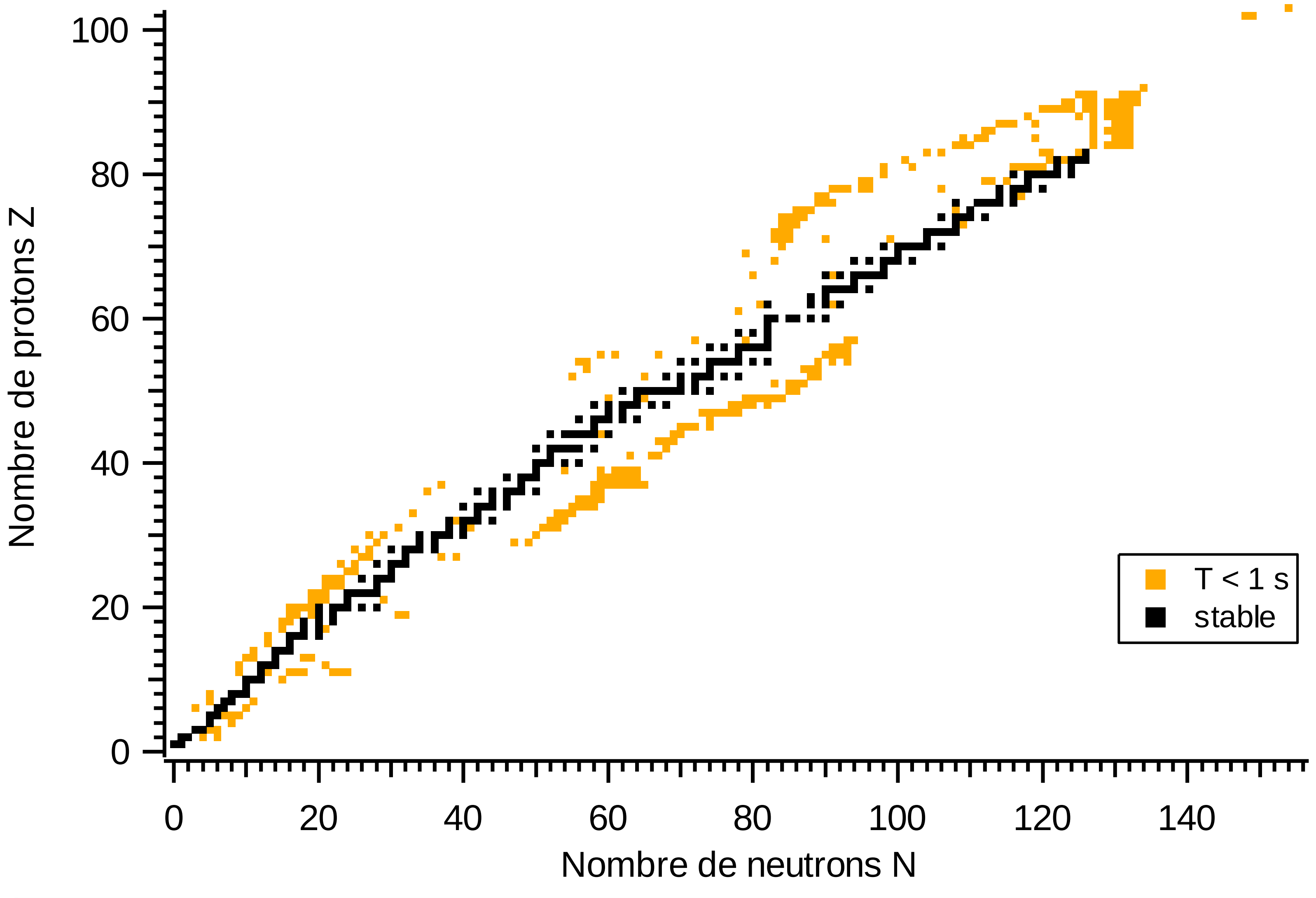

Nombre de protons Z
100
80
60
40
20
0
0
20
40
60
80
100
120
140
Nombre de neutrons N
T < 1 h
stable

$T_{1/2} < 1$ min



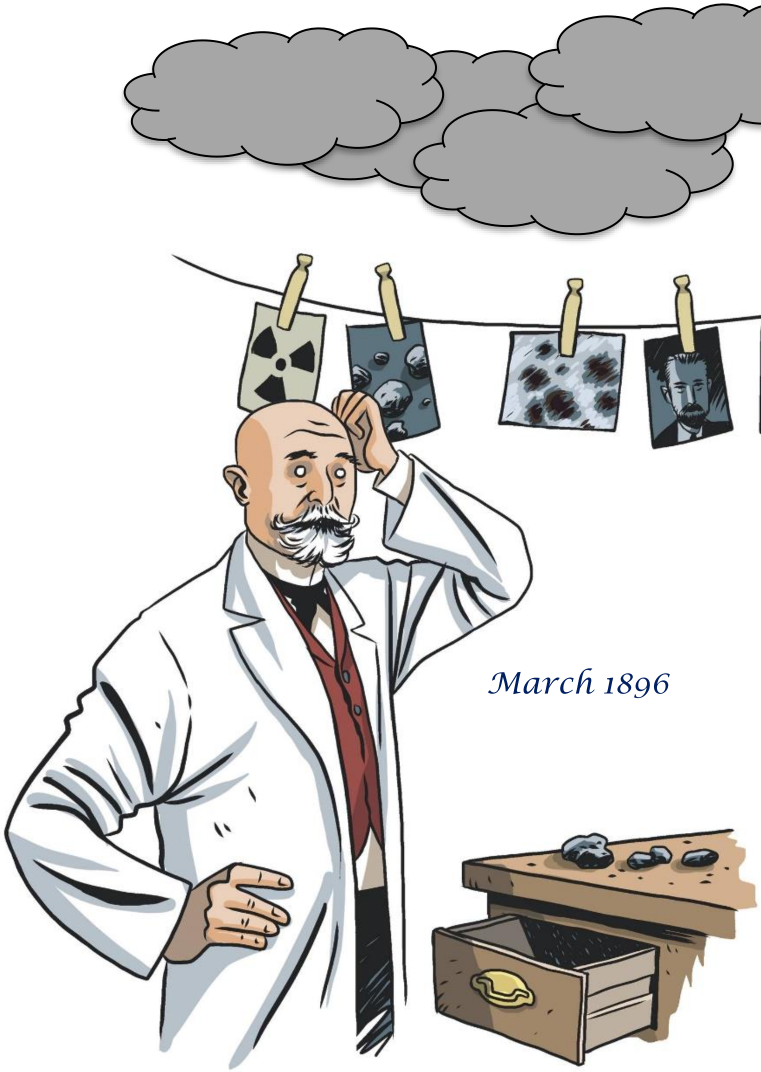
100
80
60
40
20
0
Nombre de protons Z
0
20
40
60
80
100
120
140
Nombre de neutrons N
T < 1 min
stable

$T_{1/2} < 1$ 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

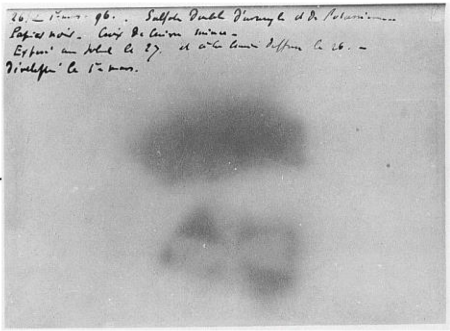
Radioactivity: History lesson



March 1896

Image credit: nobelprize.org

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

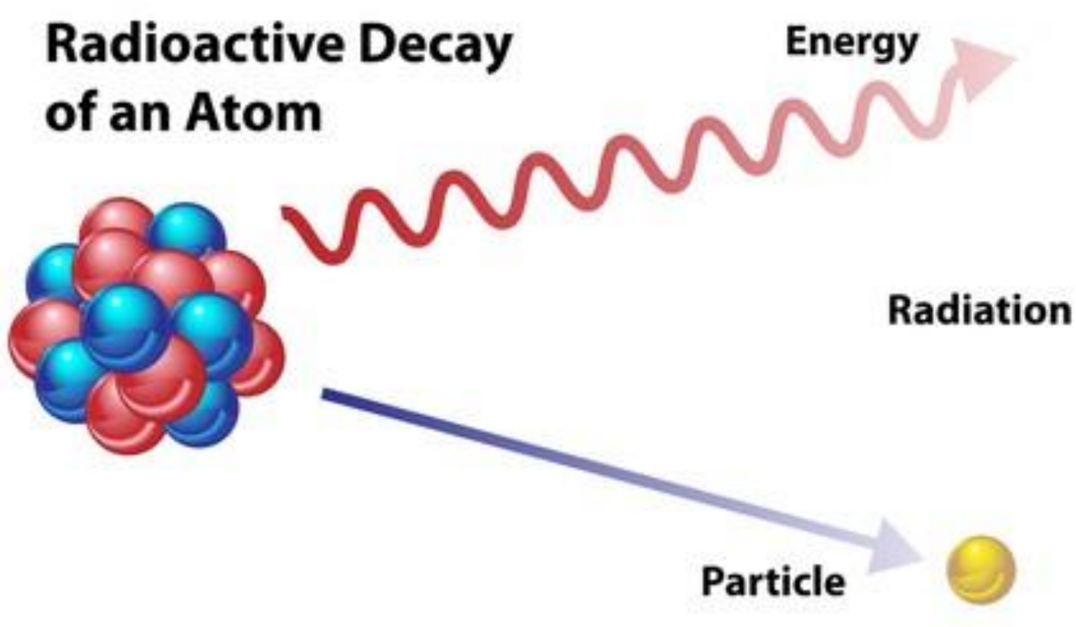
Marie Curie

Pierre Curie

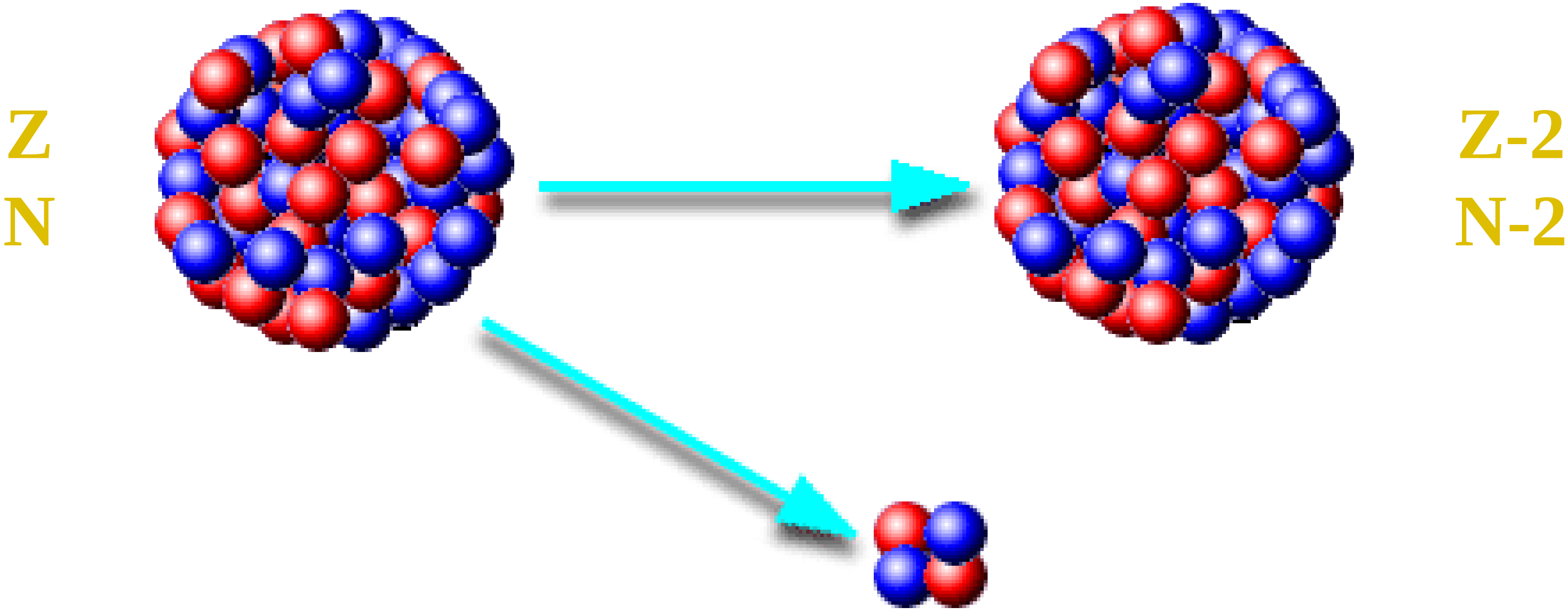
1903 Nobel Prize

Types of radioactive decay

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



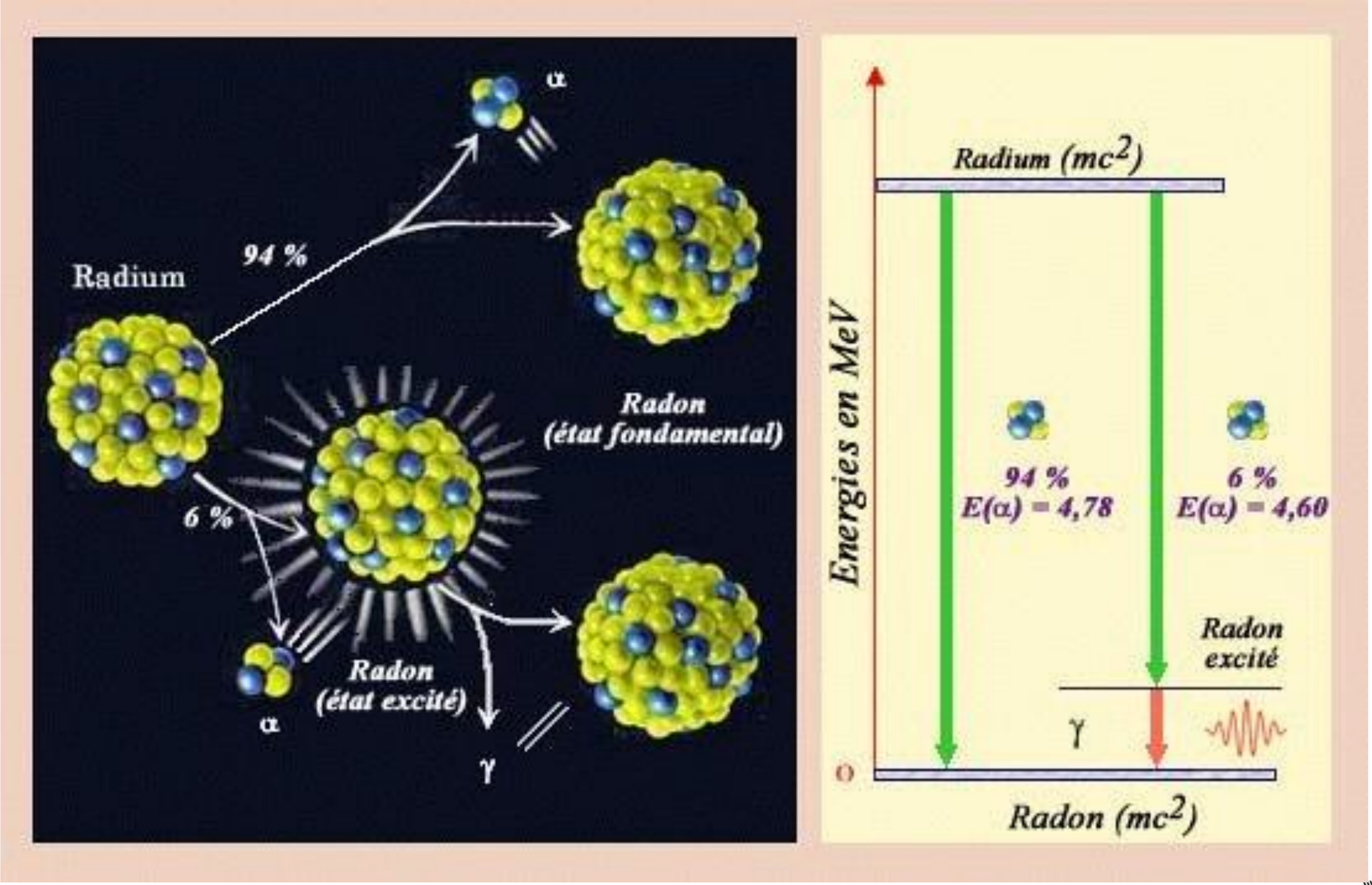
α decay



$$\alpha\text{-particle} = {}^{4}_{2}\mathrm{He}$$

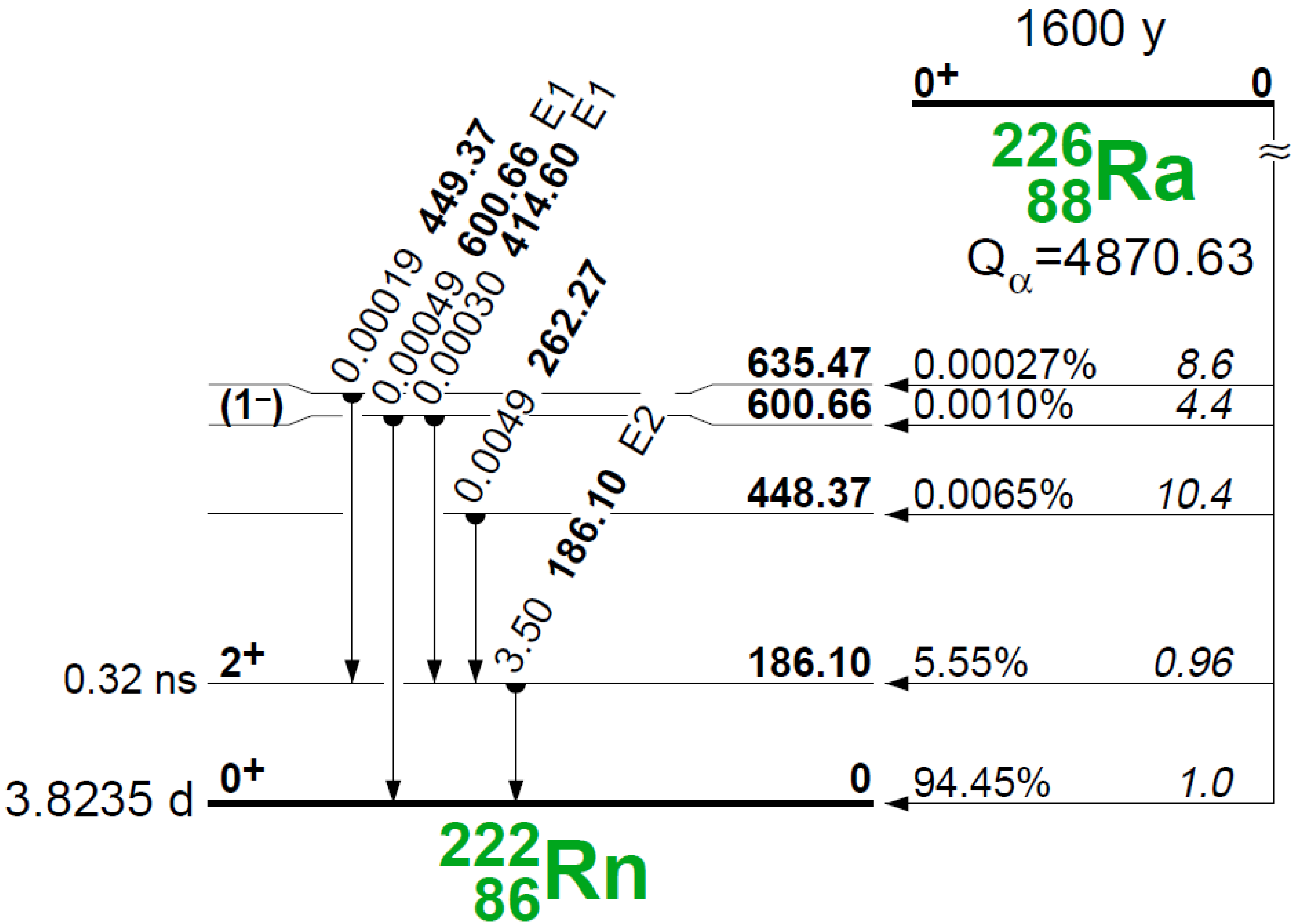
α decay

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



α decay

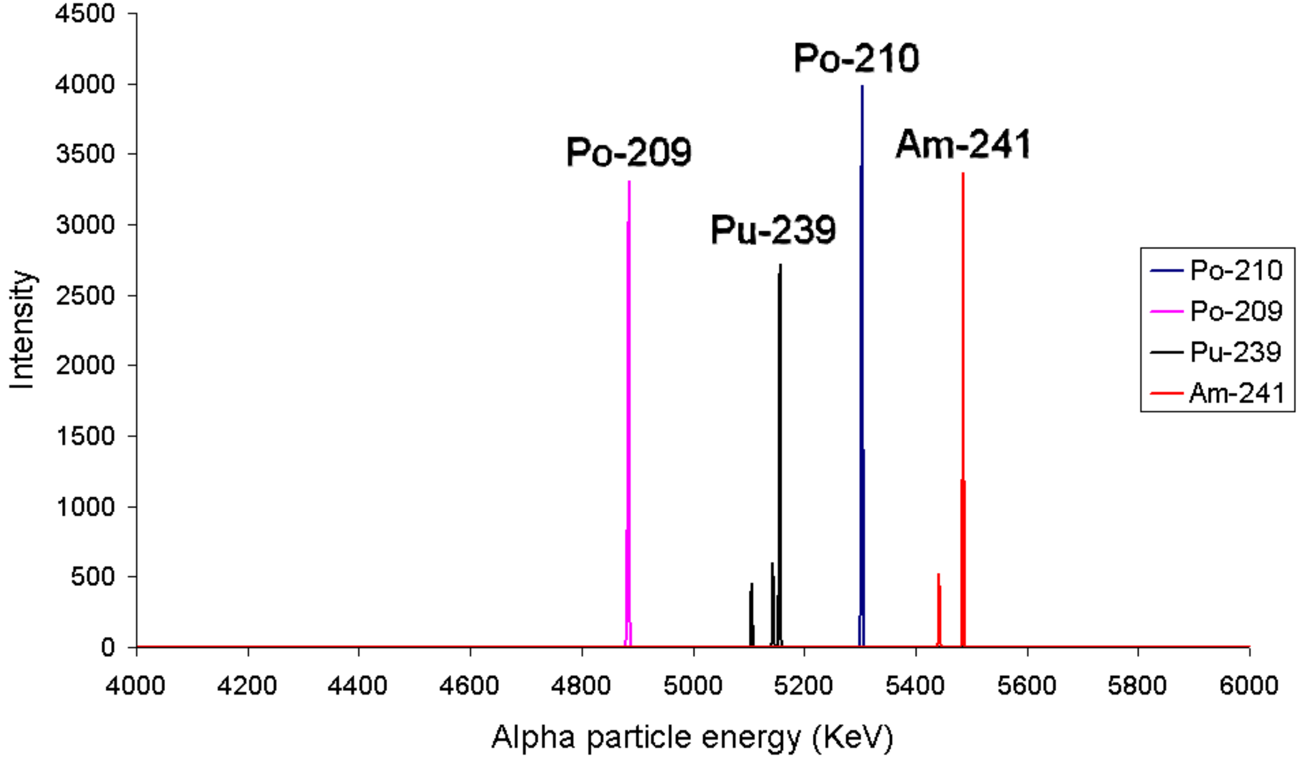
- Example of alpha decay: Ra-226 → Rn-222



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

α decay

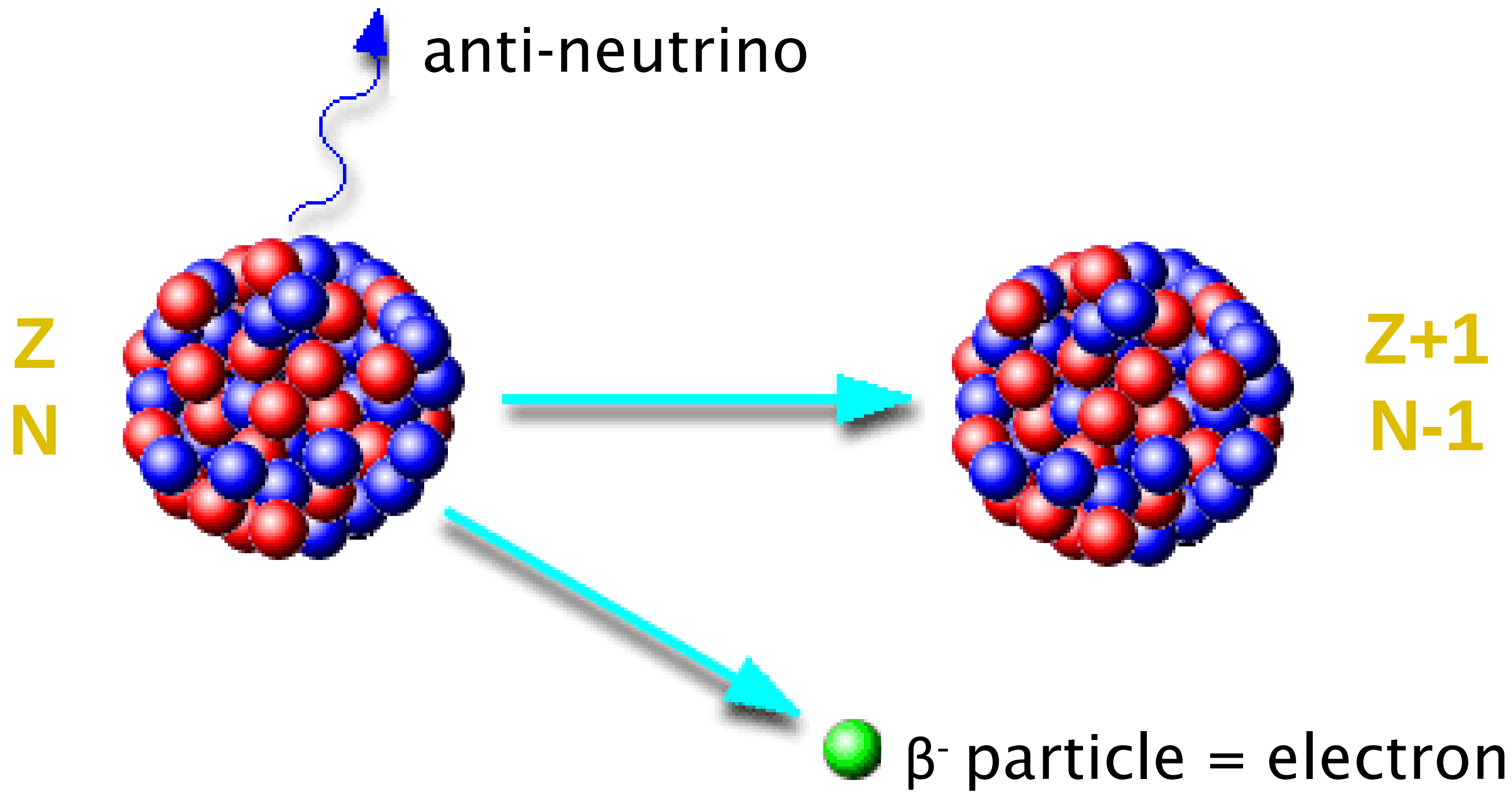
- The energy of emitted α-particle



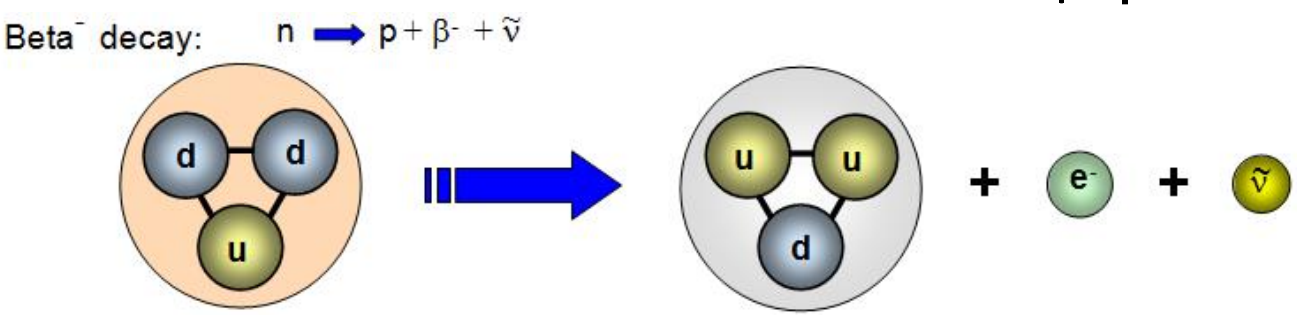
- Alpha decay involves the emission of an alpha particle (helium nucleus: 2 protons + 2 neutrons). The energy spectrum consists of lines that can be used to identify nuclides by spectrometry.

canton de vaud

β^- decay



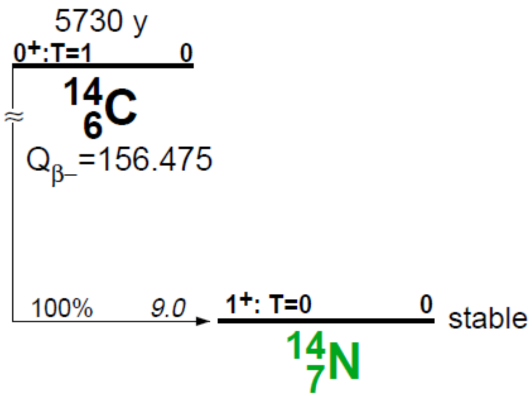
anti-neutrino
Z
N
Z+1
N-1
β- particle = electron



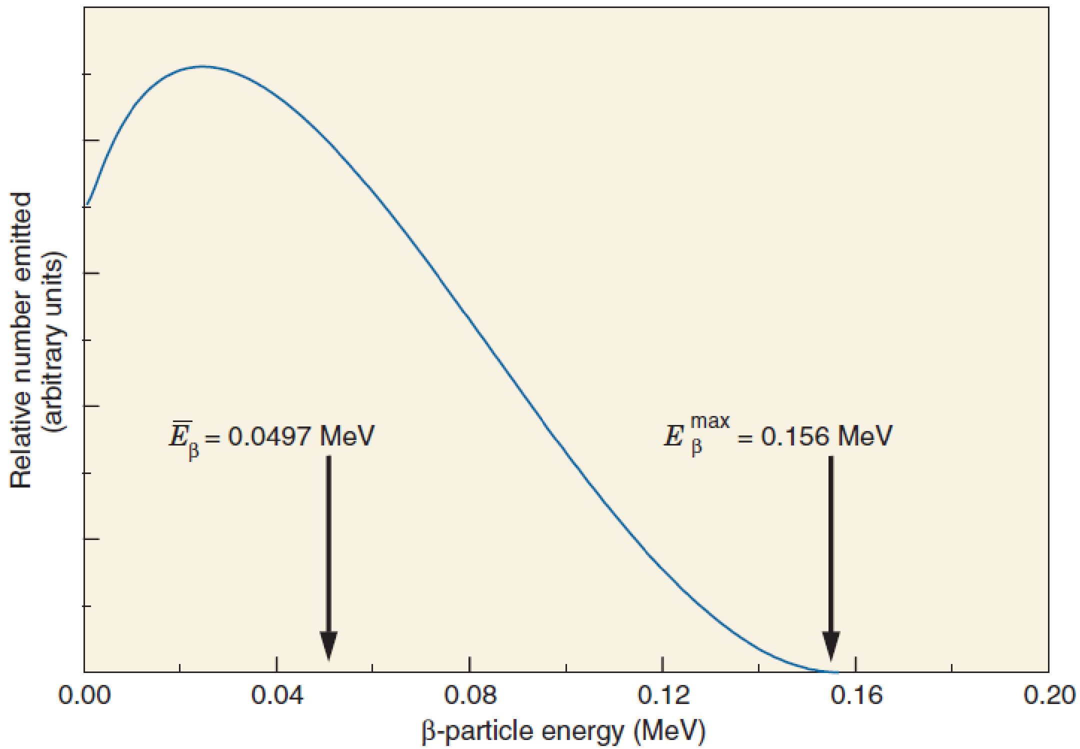
Beta- decay:
n → p + β- + ν̃
d
d
u
u
u
d
+
e-
+
ν̃

β^- decay

- Example of β^- decay: C-14 → N-14



- β^- decay involves the transformation, **inside the nucleus**, 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



Radioactive decay

Q4: Which of the following nuclear transformations of the radionuclide E describes the beta minus (β-) decay?

1) ${}^{A}_{Z}E_{N} \rightarrow {}^{A-4}_{Z-2}E_{N-2}$

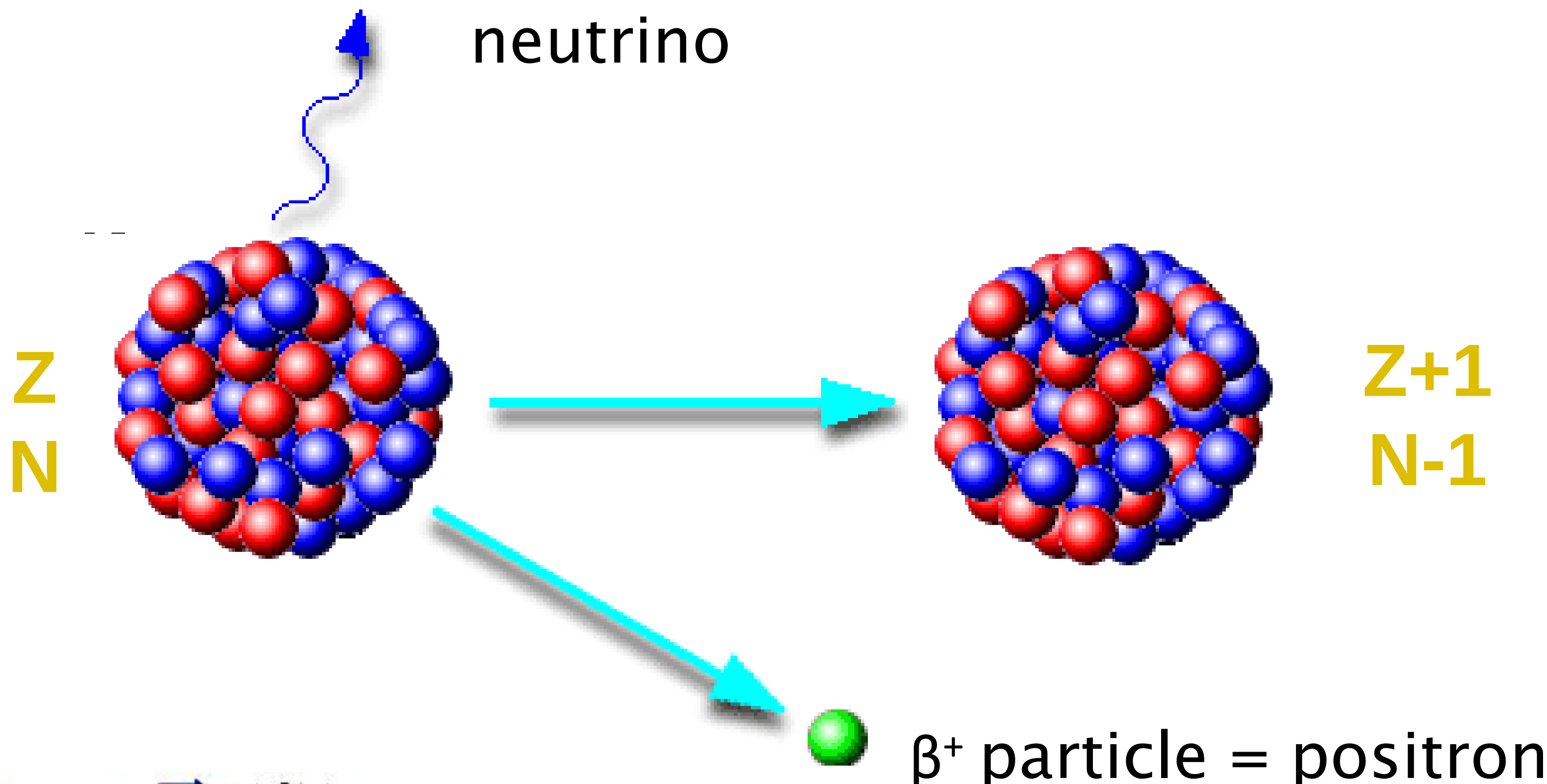
2) ${}^{A}_{Z}E_{N} \rightarrow {}^{\quad A}_{Z+1}E_{N-1}$

3) ${}^{A}_{Z}E_{N} * \rightarrow {}^{A}_{Z}E_{N}$

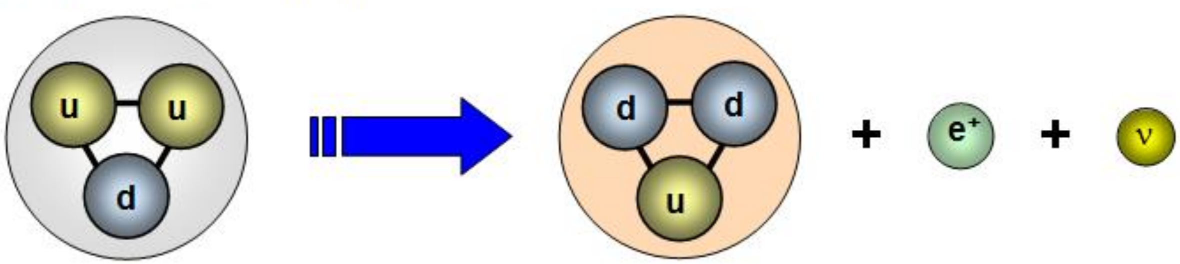
4) ${}^{A}_{Z}E_{N} \rightarrow {}^{\quad A}_{Z-1}E_{N+1}$

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

β^+ decay

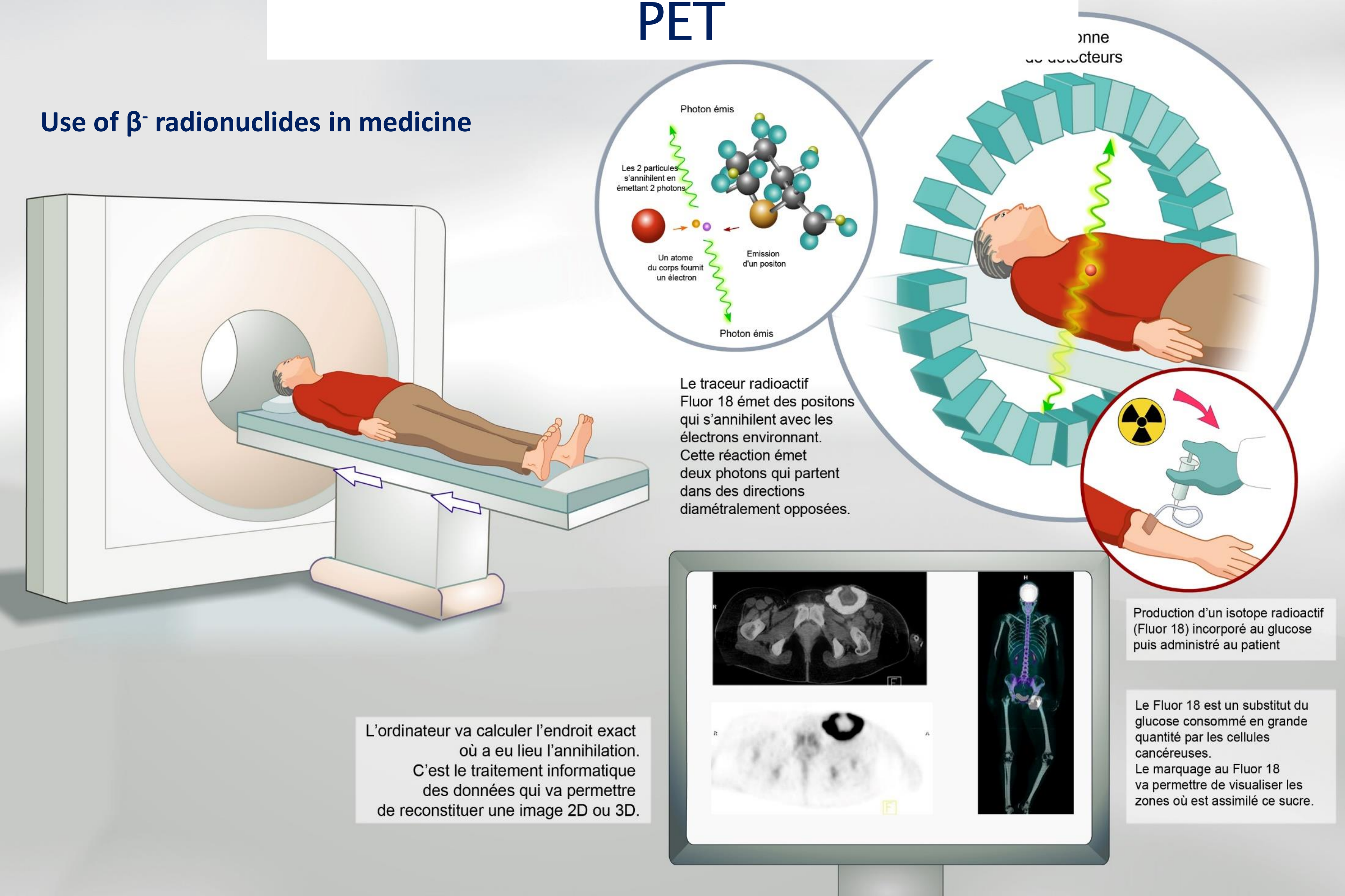


Beta$^+$ decay: p → n + β^+ + ν



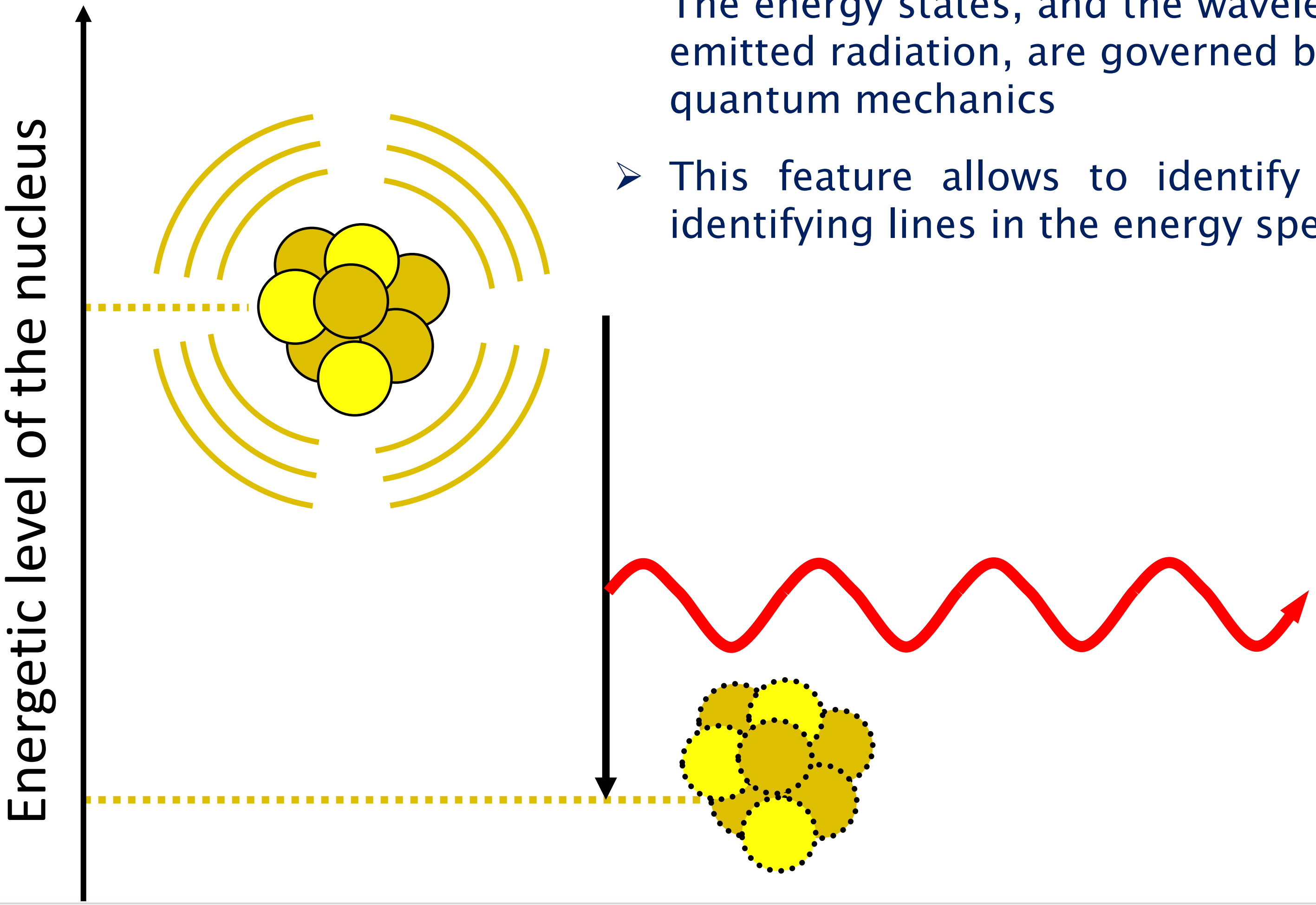
Positron emission tomography
PET

Use of β⁻ radionuclides in medicine



© CEA / Corinne Beurtey

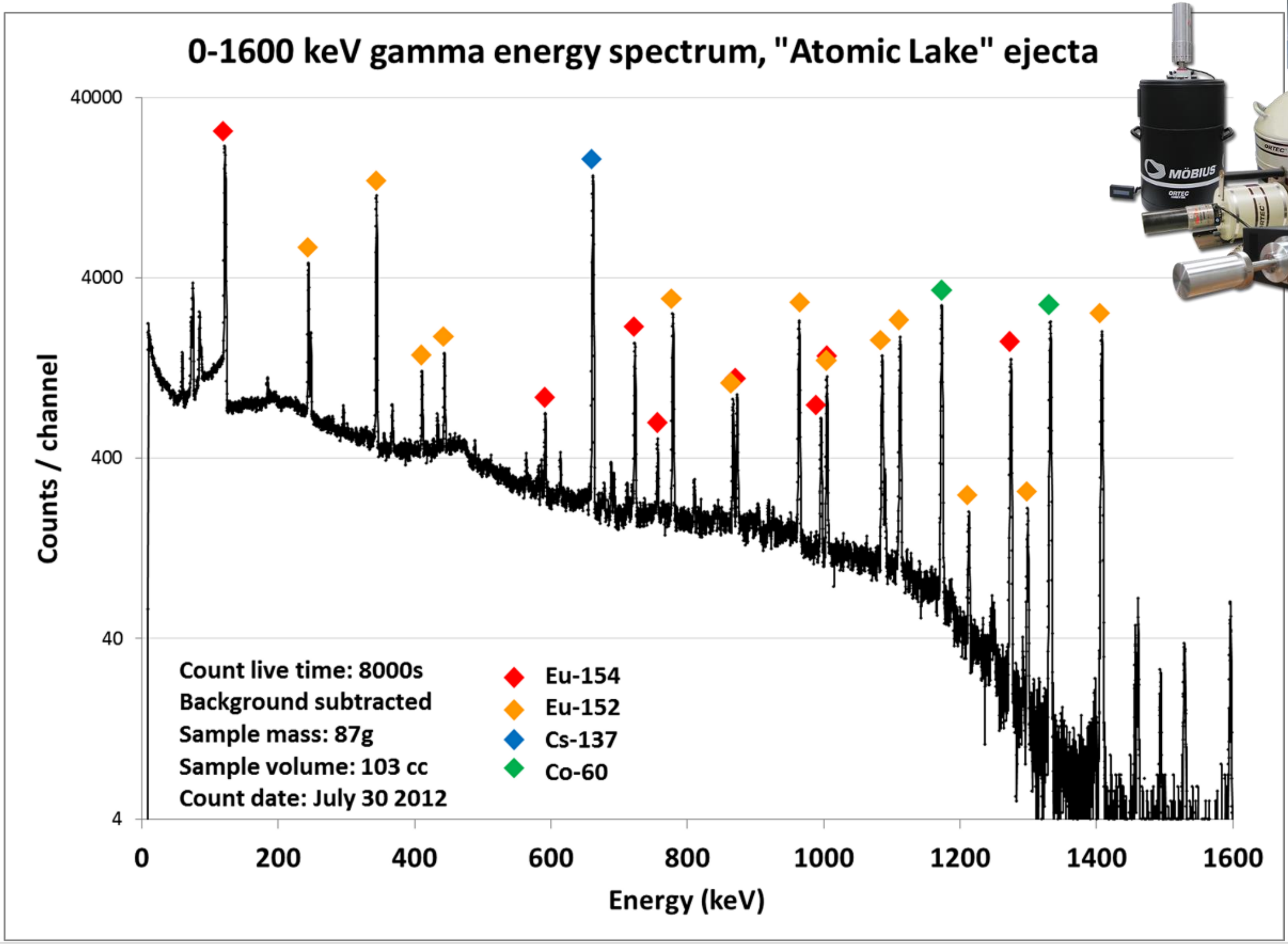
Types of radioactive decay: **γ decay**



- 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.

Types of radioactive decay: **γ decay**

- Identification of elements by gamma spectrometry

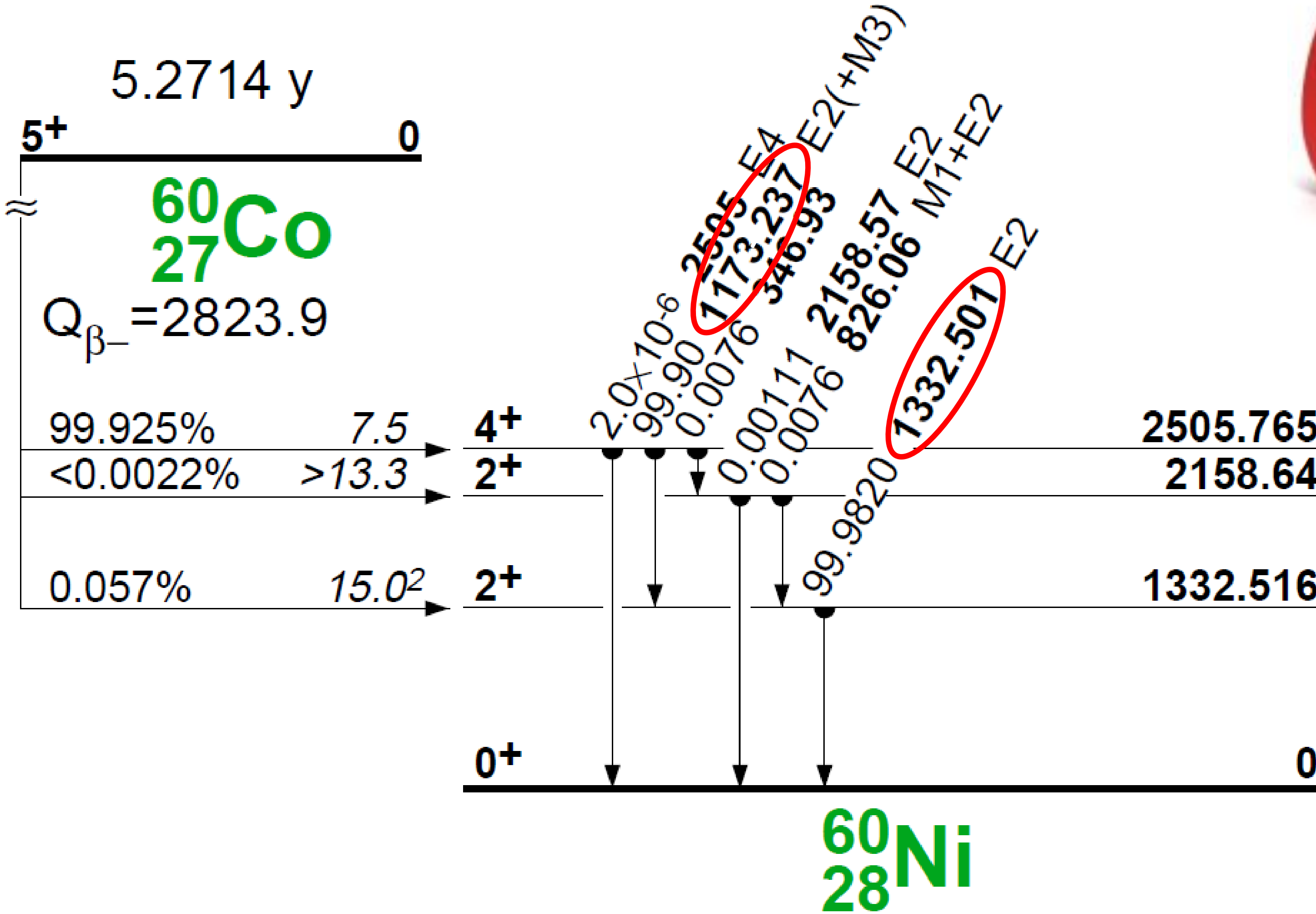


canton de vaud

CHUV

Radioactive decay

Q6: What is the mean number of photons having energies between 1 and 2 MeV emitted after 10'000 decays of Co-60?

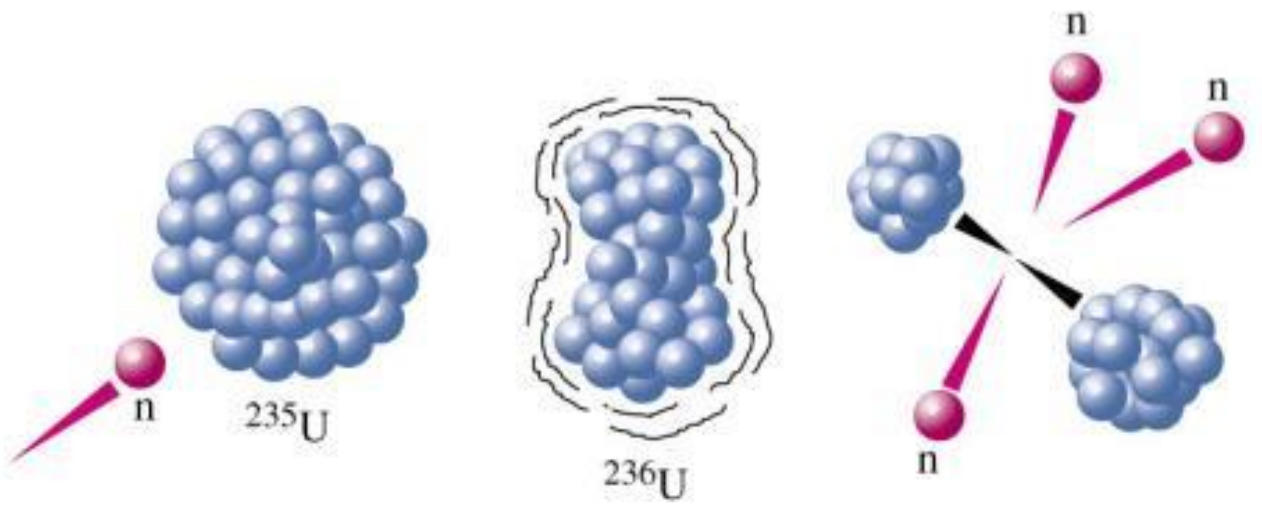


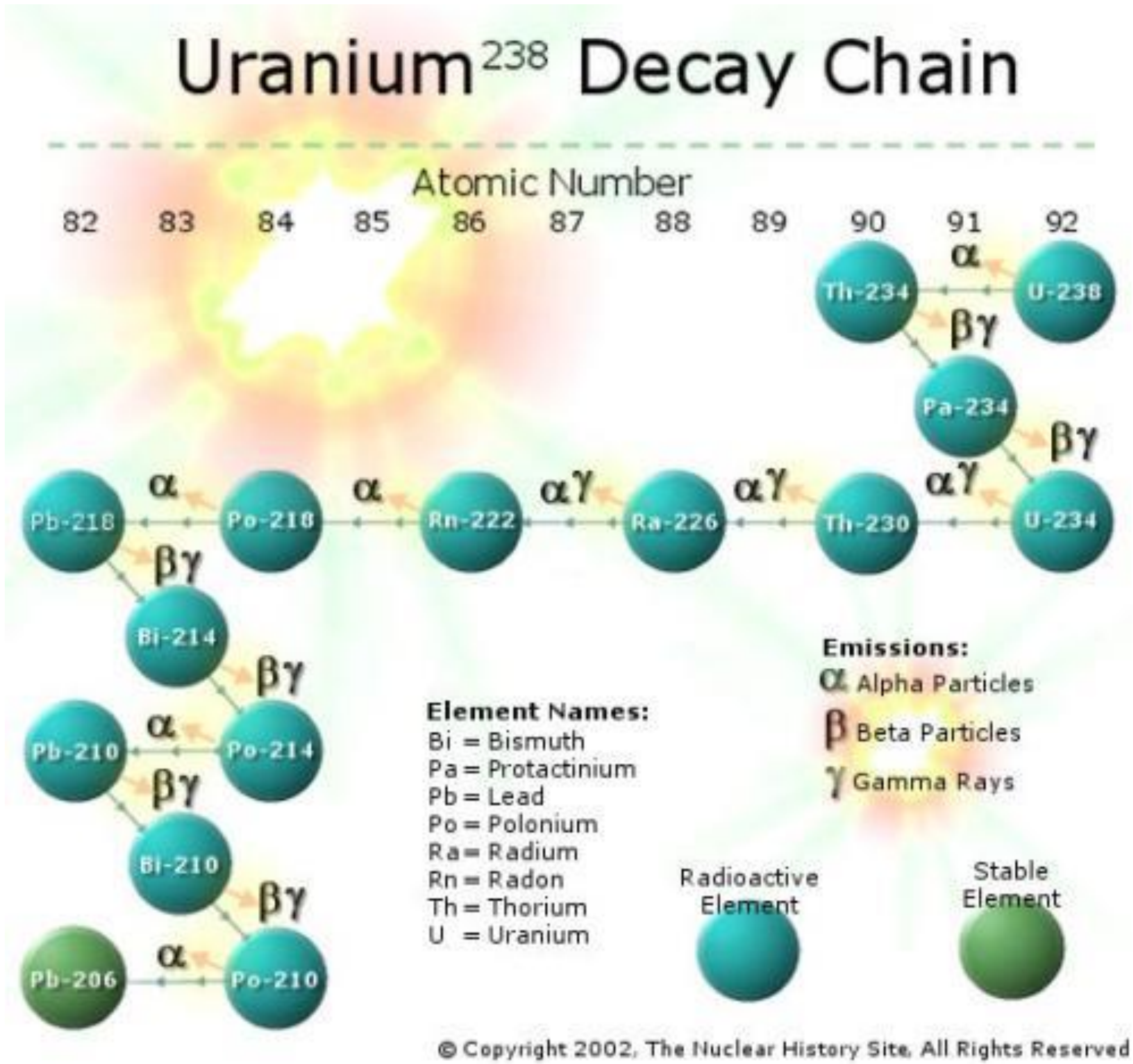
R. B. Firestone, Table of Isotopes, Wiley-Interscience, 1996

Types of radioactive decay: **fission**

- Fission is typically caused by the capture of a neutron (although it can be spontaneous as well) in a small number of very heavy nuclei, called fissile, weakened by too many nucleons. These very large nuclei then split into more stable nuclei, releasing energy by fission

- Examples of fissile nuclei: U-235, Pu-239, U-233

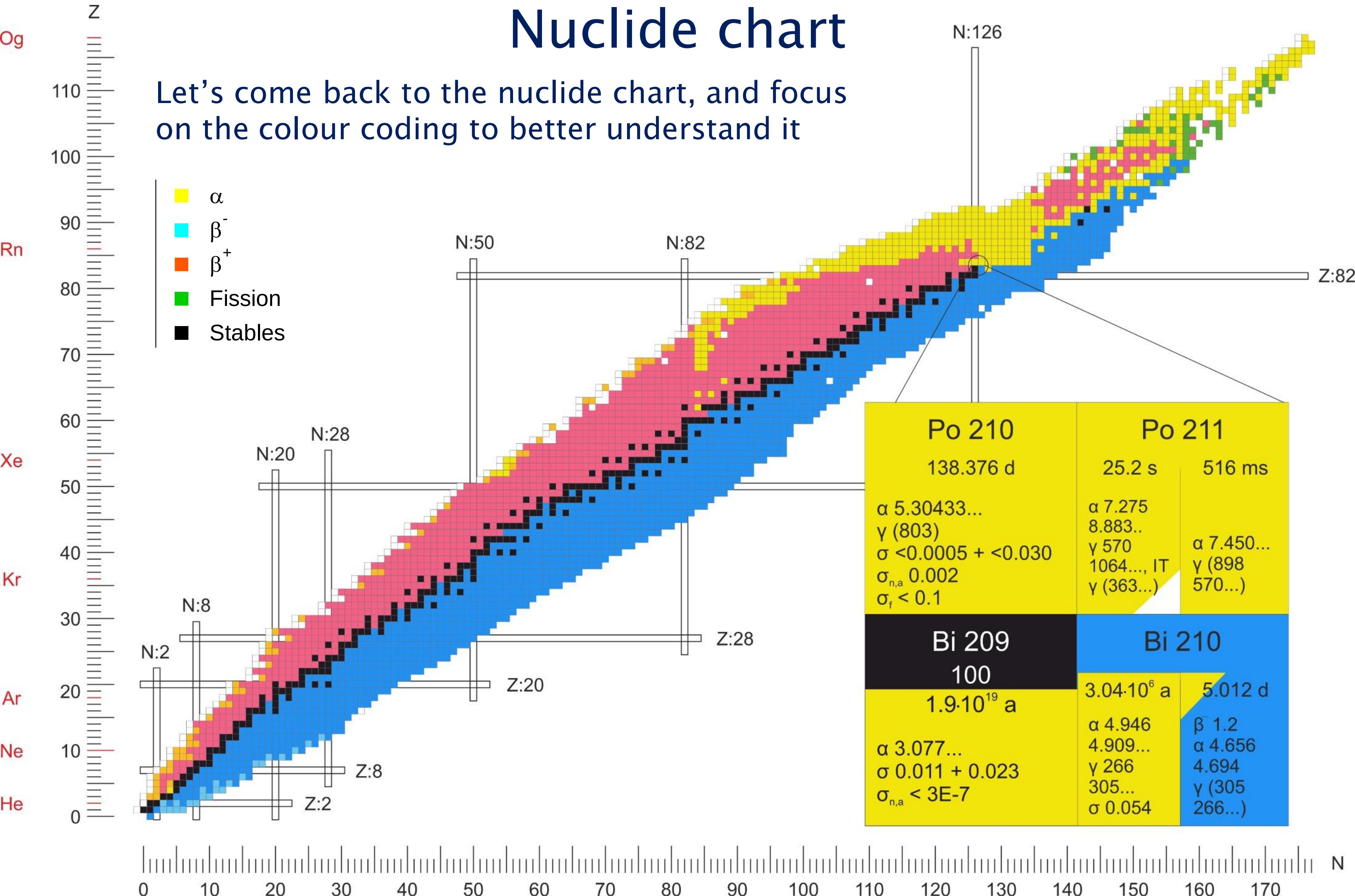




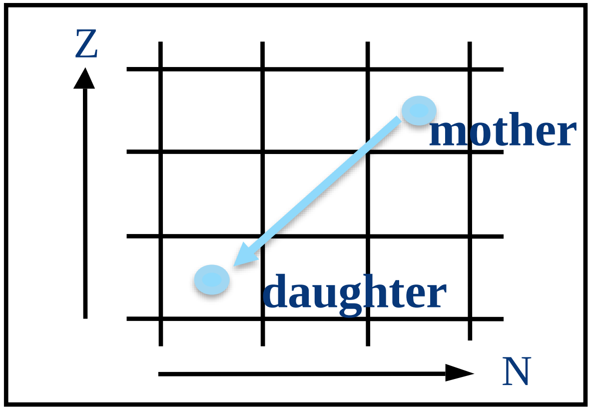
Uranium 238 Decay Chain
Atomic Number
82 83 84 85 86 87 88 89 90 91 92
Th-234
U-238
Pa-234
Pb-218
Po-218
Rn-222
Ra-226
Th-230
U-234
Bi-214
Pb-210
Po-214
Bi-210
Pb-206
Po-210
α
βγ
αγ
Element Names:
Bi = Bismuth
Pa = Protactinium
Pb = Lead
Po = Polonium
Ra = Radium
Rn = Radon
Th = Thorium
U = Uranium
Emissions:
α Alpha Particles
β Beta Particles
γ Gamma Rays
Radioactive Element
Stable Element
© Copyright 2002, The Nuclear History Site, All Rights Reserved

Nuclide chart

Let’s come back to the nuclide chart, and focus on the colour coding to better understand it

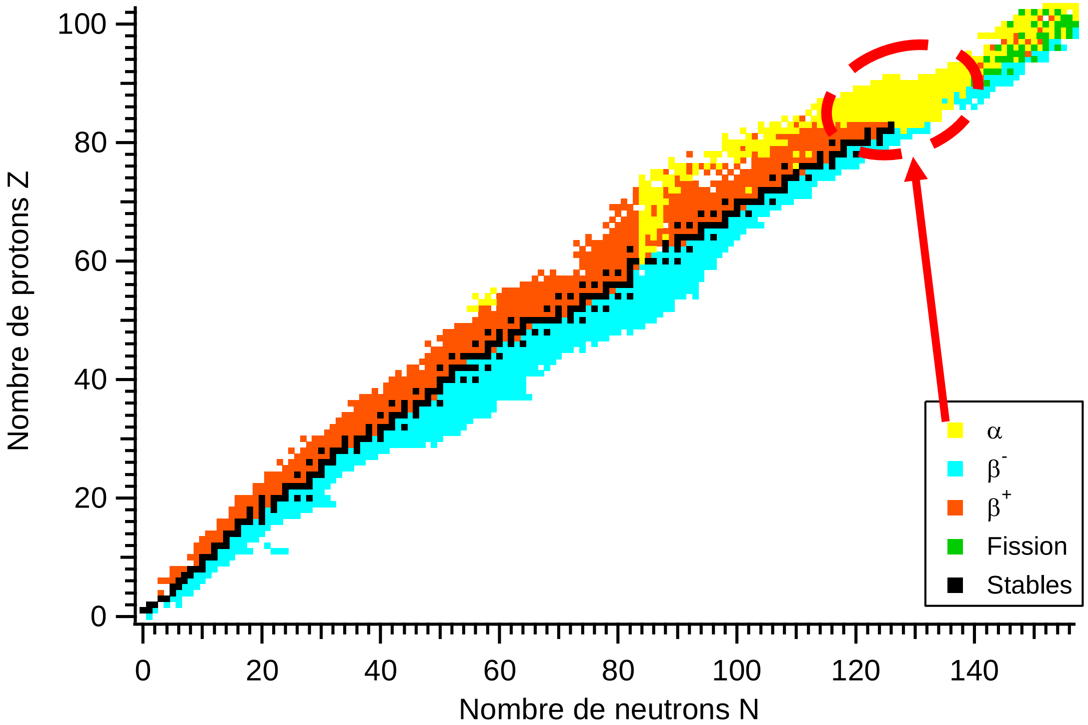


Nuclide chart: α decay



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

particule α



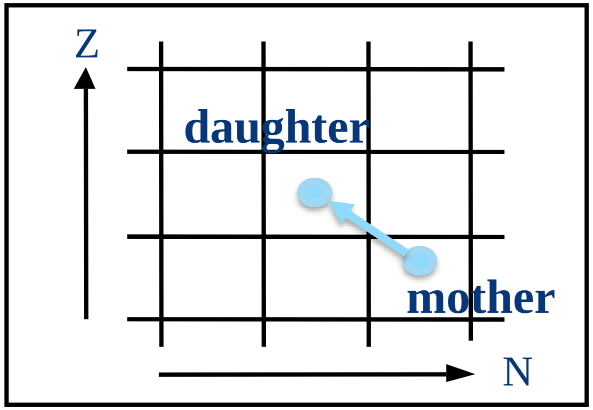
examples:

Rn-222

Am-241

U-238

Nuclide chart: β⁻ decay

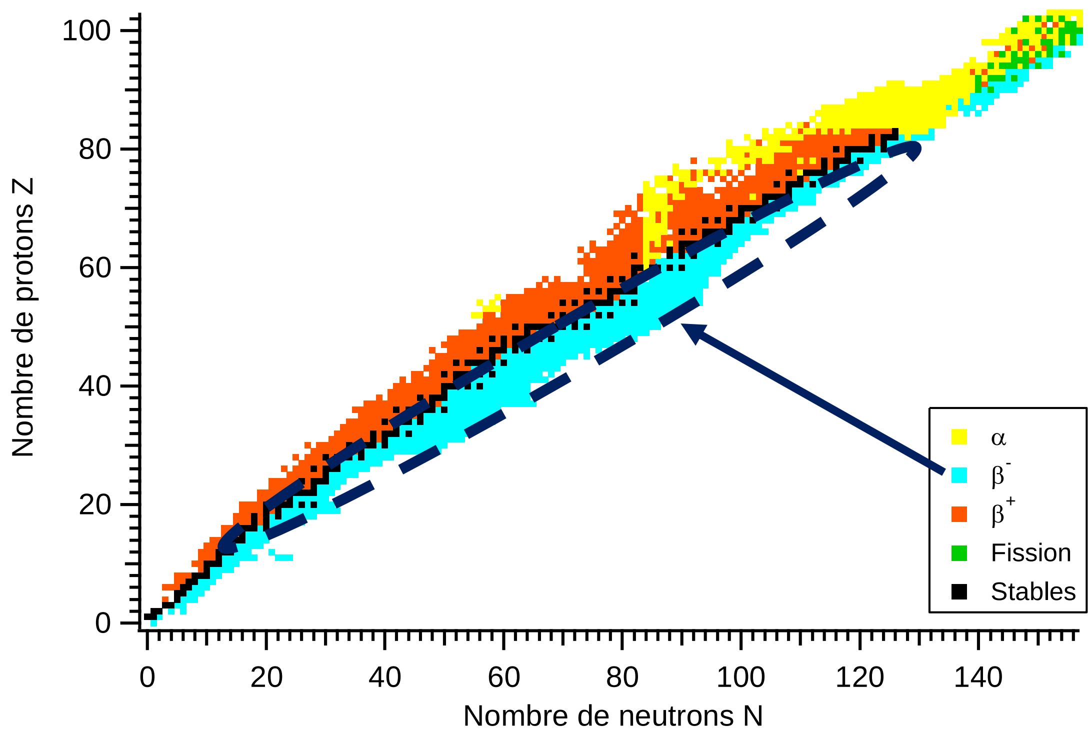


$${}^{A}_{Z}E_{N} \rightarrow {}^{A}_{Z+1}E_{N-1} + \beta^{-} + \bar{\nu}$$

électron

anti-neutrino

➢ **Neutron** *transforms* into a **proton**



examples:

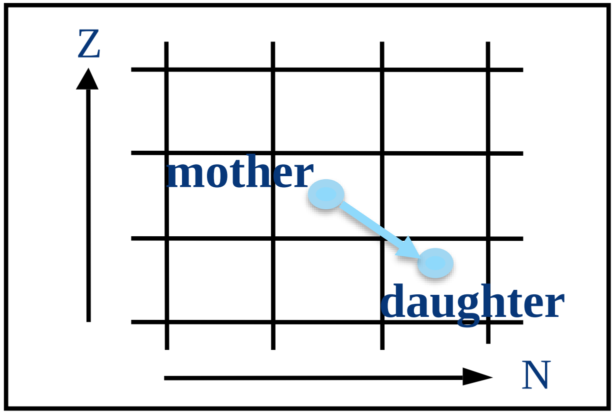
H-3

C-14

K-40

Bi-210

Nuclide chart: β^+ decay

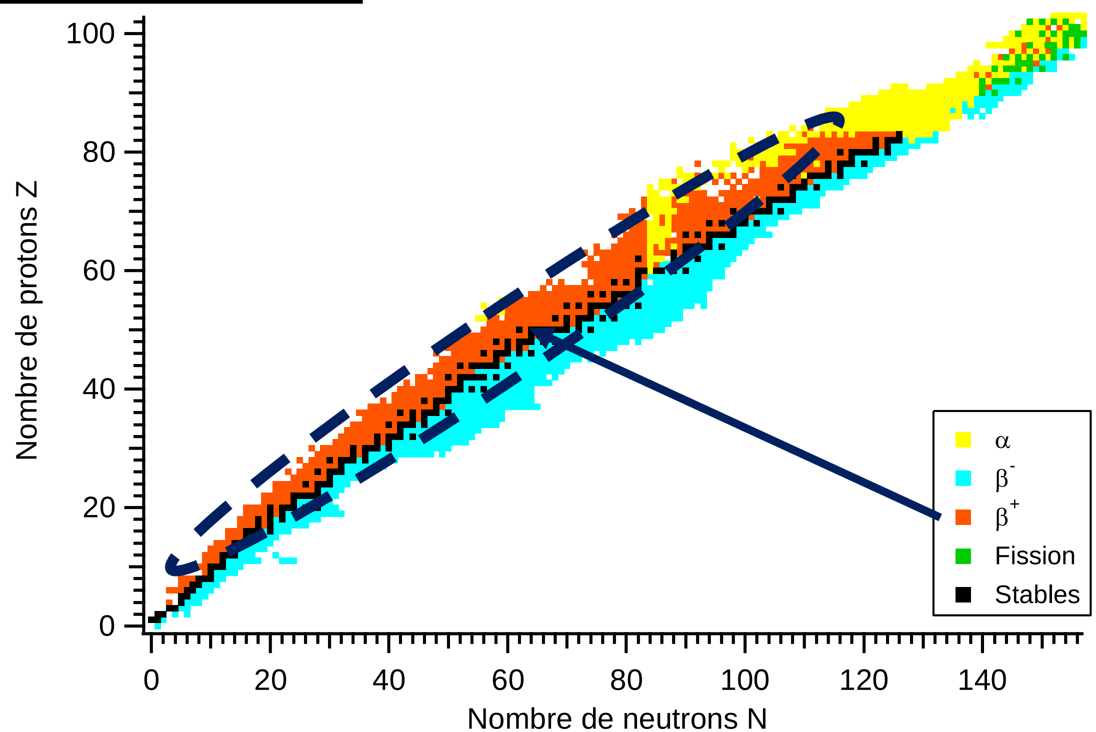


$$ {}^{A}_{Z}E_{N} \rightarrow {}^{A}_{Z-1}E_{N+1} + \beta^{+} + \upsilon $$

positron

neutrino

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



examples:

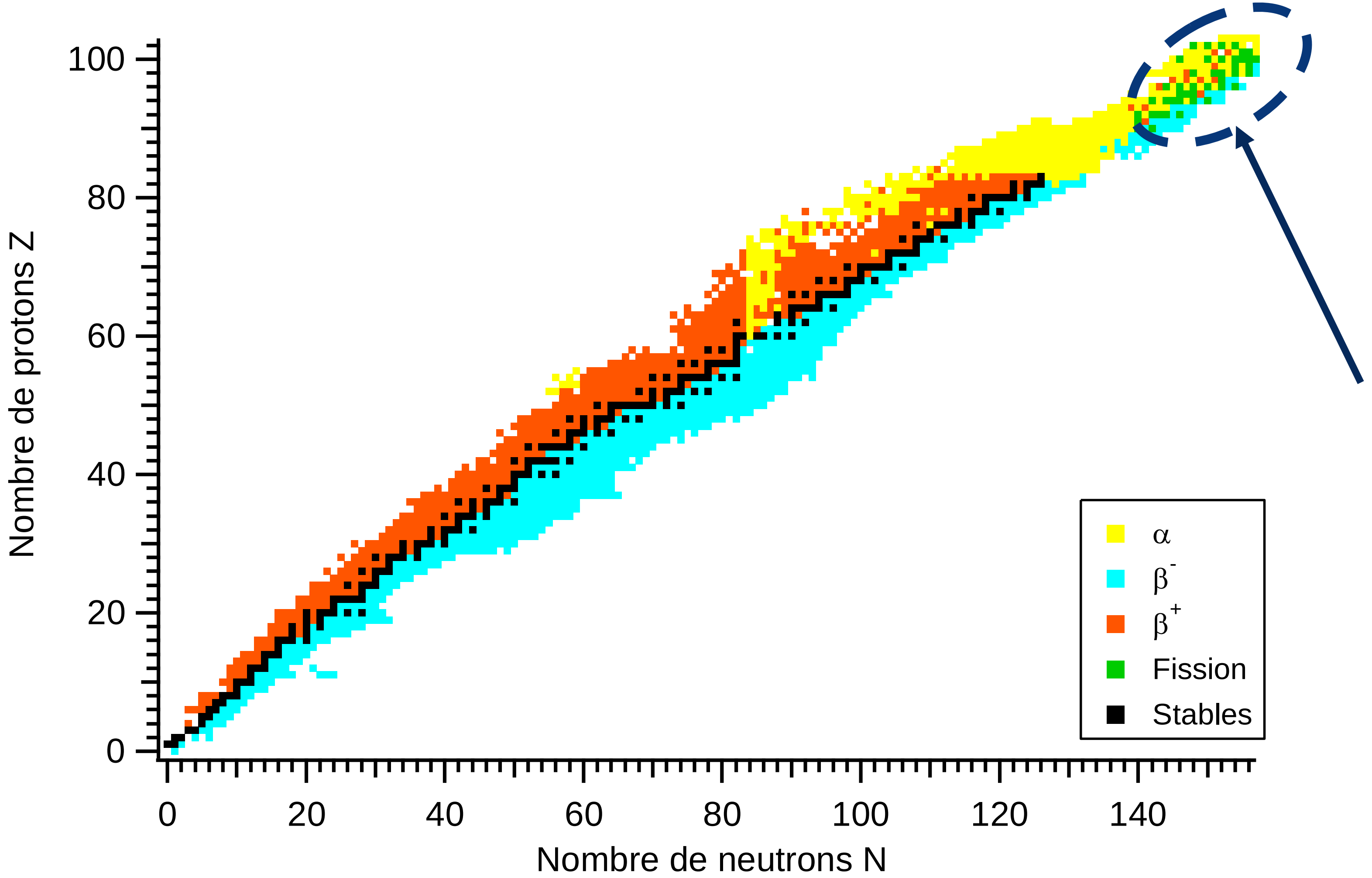
C-11

N-13

O-15

F-18

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	

82

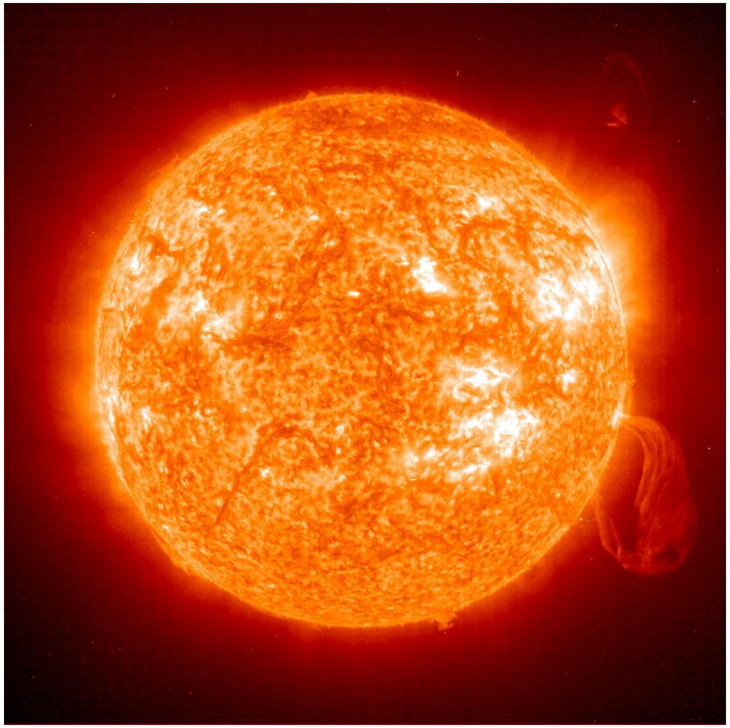
Radioactivity around us: **Primordial radionuclides**

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

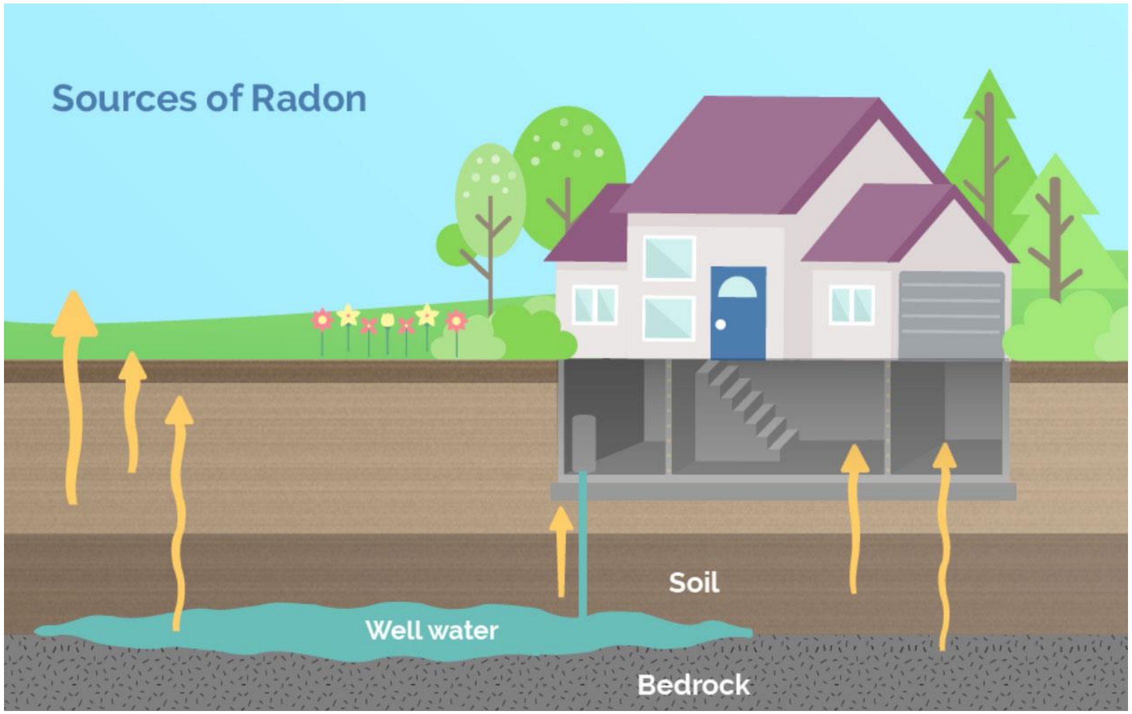
  Uranium-238 ($T_{1/2}$=4.5 billion years)

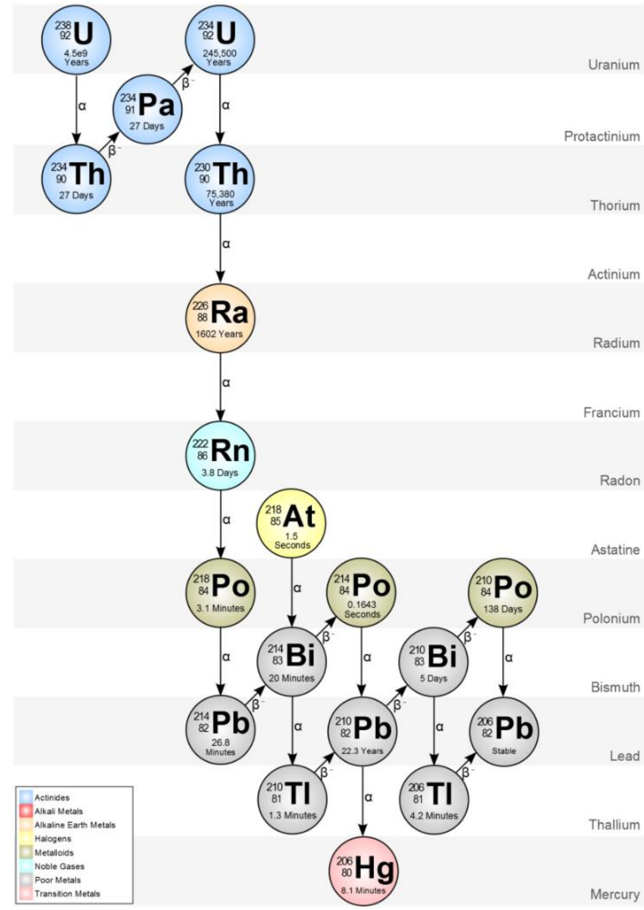
  Thorium 232 ($T_{1/2}$=14 billion years)

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



Radioactivity around us: **Radon**





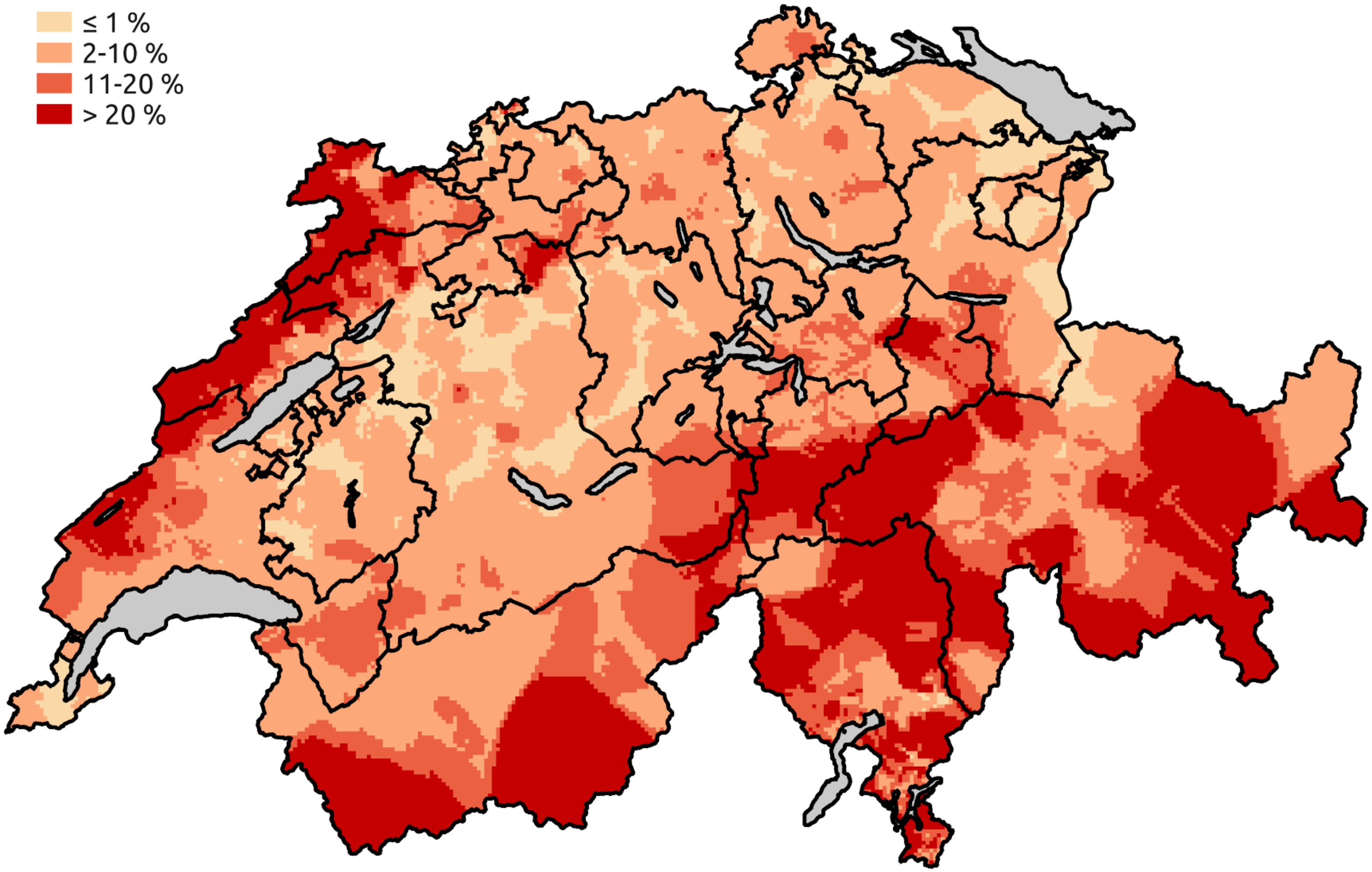
- Exposure to Rn-222 ($T_{1/2}$ = 3.8 days) is the largest naturally occurring environmental hazard

canton de vaud

CHUV

Radon in Switzerland

➢ Probability of exceeding the reference value:



Federal Office of Public Health (FOPH)

Radioactive decay

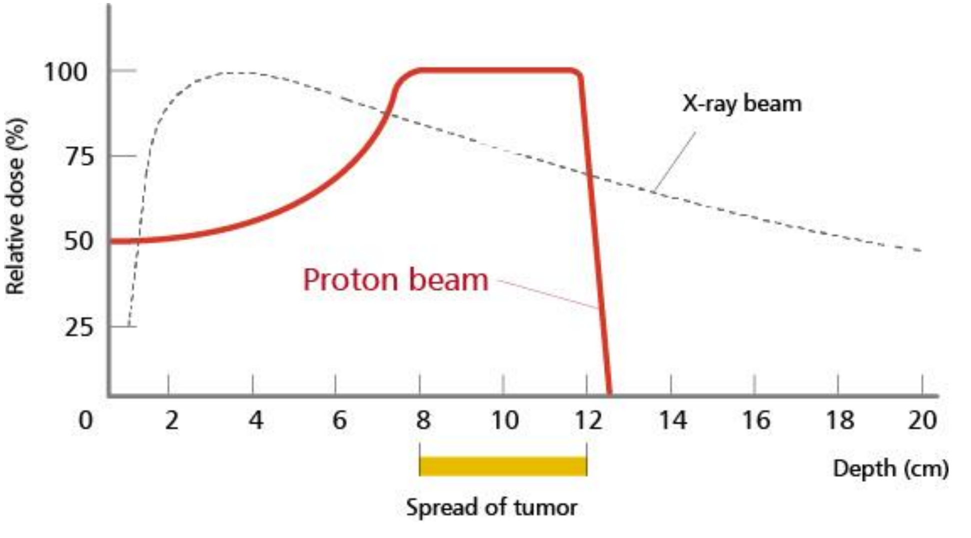
Q7: Which type of cancer can be caused by Rn-222 and why?

INTERACTION OF RADIATION WITH MATTER

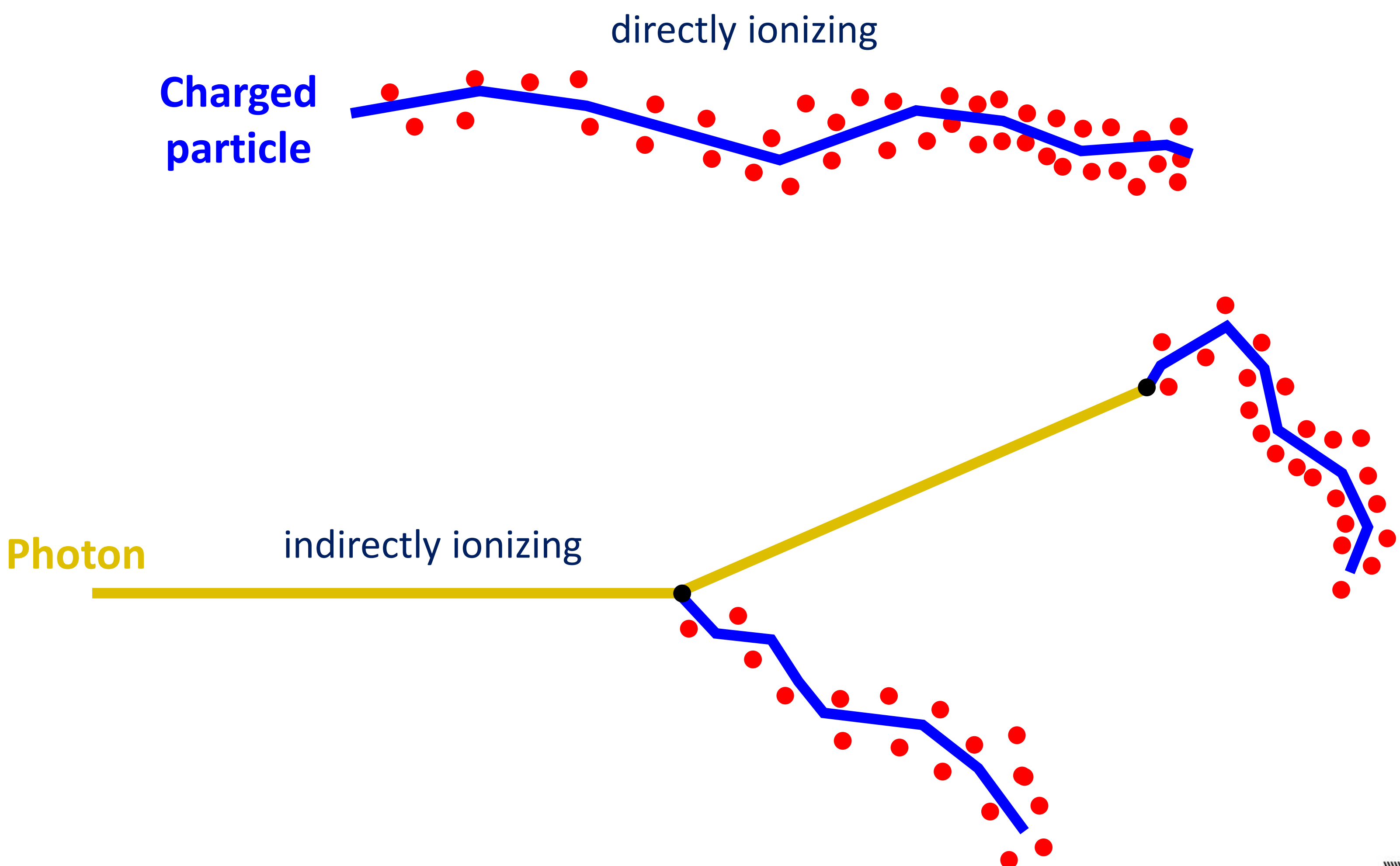
Lecture objectives

At the end of the lecture you should be able to :

- Describe how different types od radiation interact with matter
- Understand particle tracks in matter and their dependecy on particle mass and energy



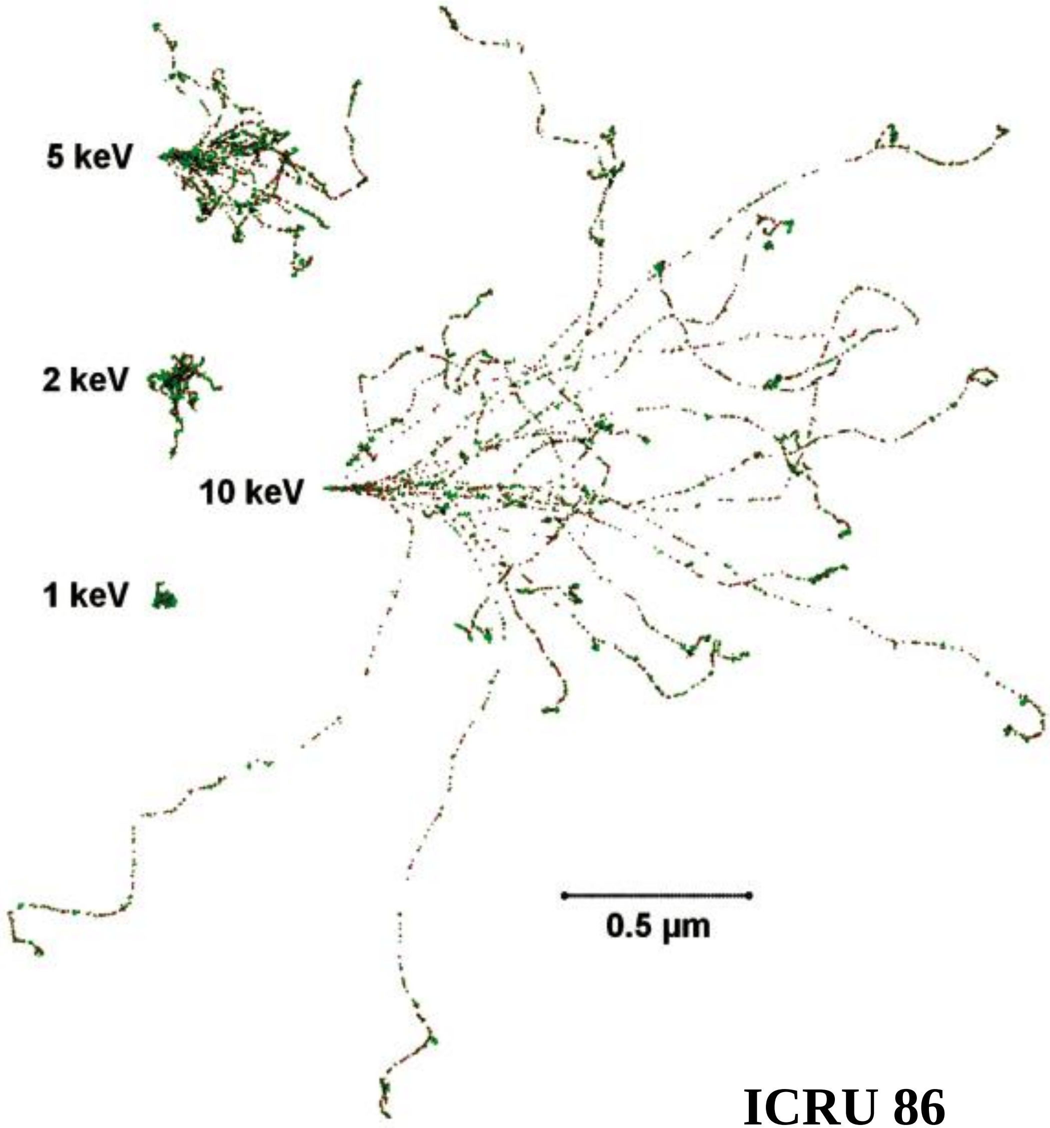
Interaction of radiation with matter



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

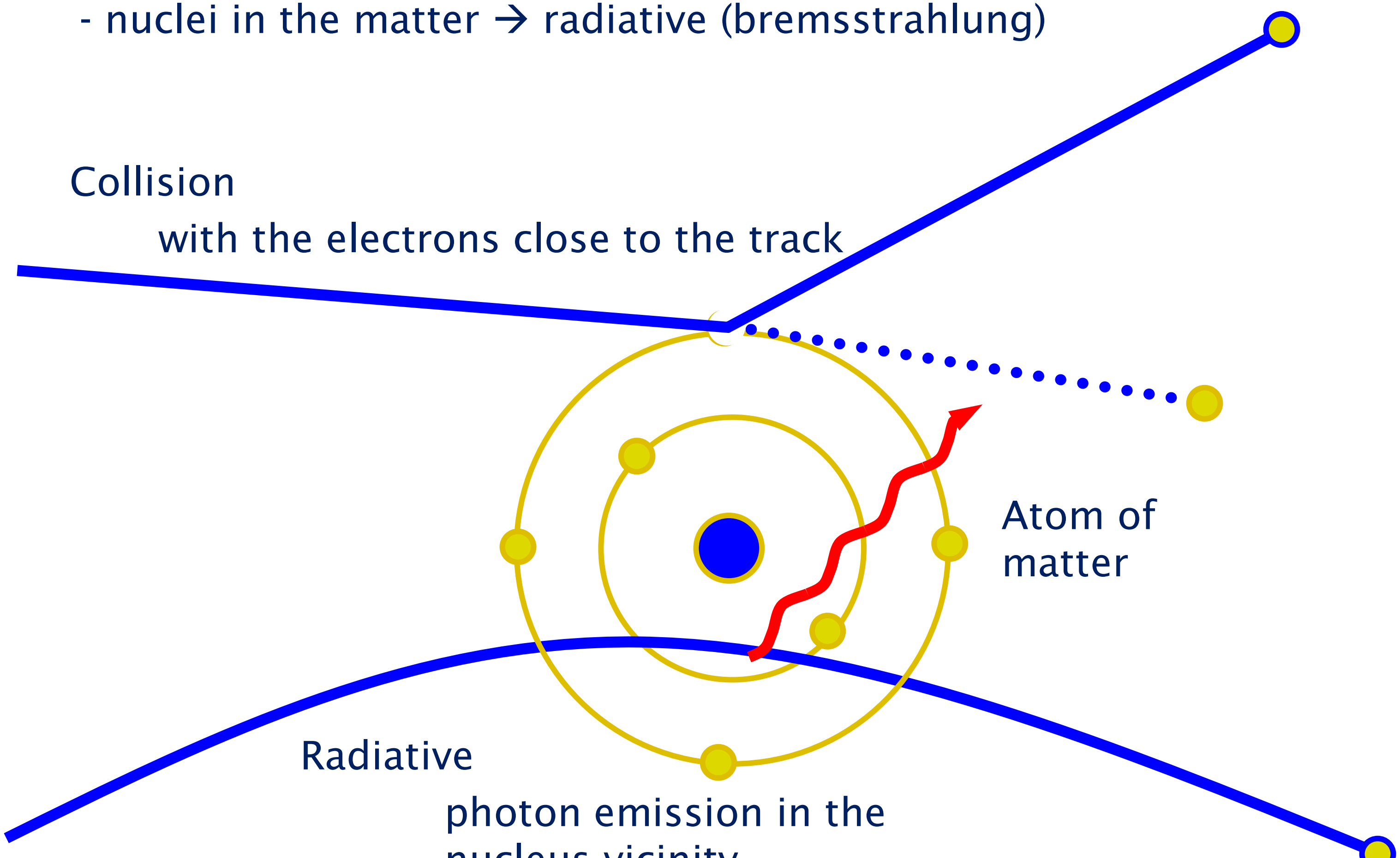


ICRU 86

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)

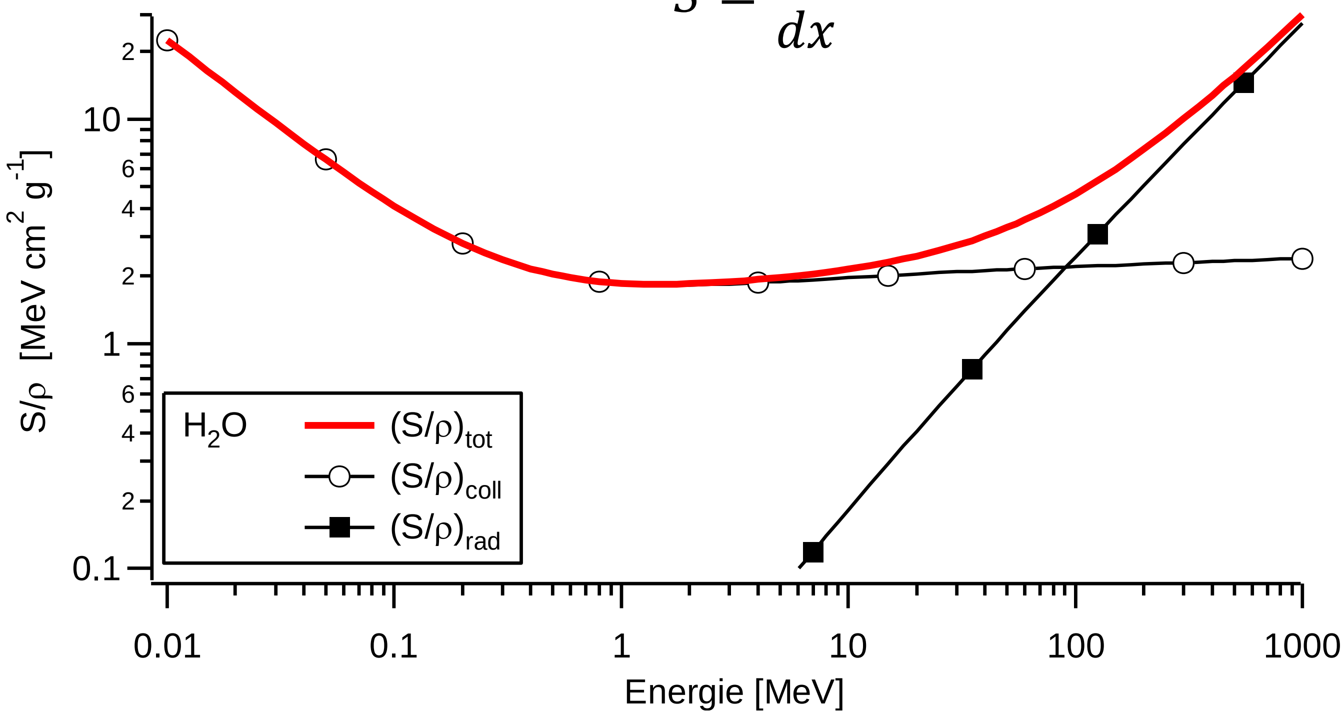


Stopping power of electrons in water

Stopping power

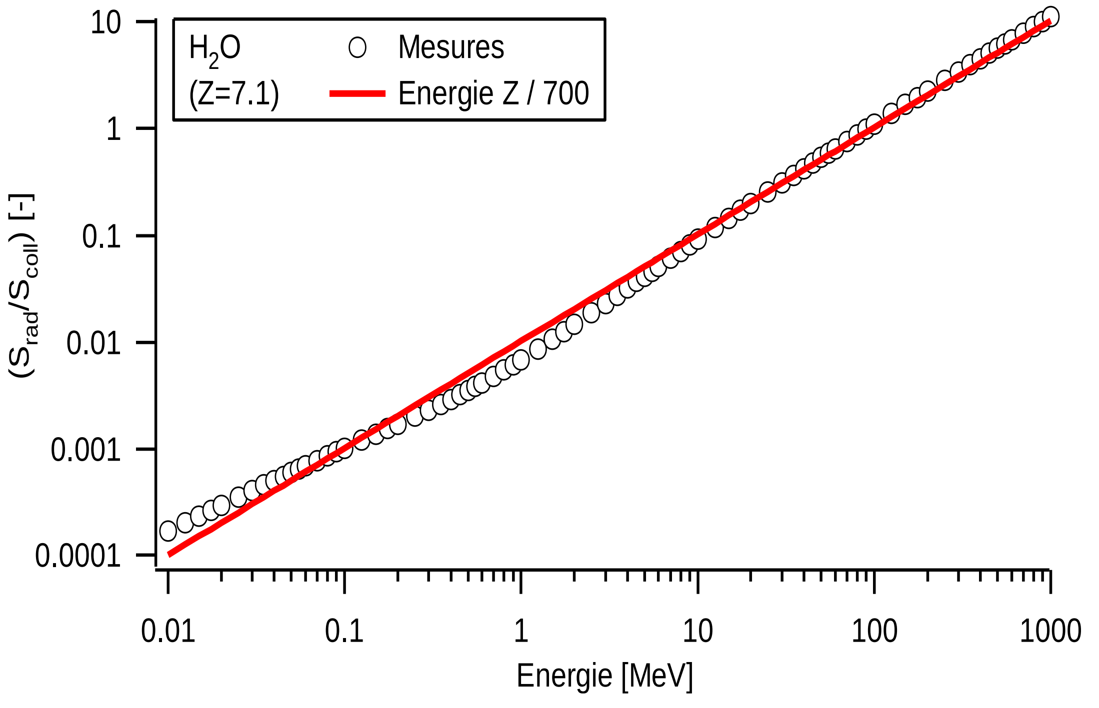
The stopping power of a material for a particle is the amount of energy that it loses per unit length along its path. The mass stopping power is stopping power normalized to the density ρ of the material

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



Radiative vs. Collision components
Dependace on electron energy

- The more protons (the higher the atomic number Z), the greater the radiative process is.

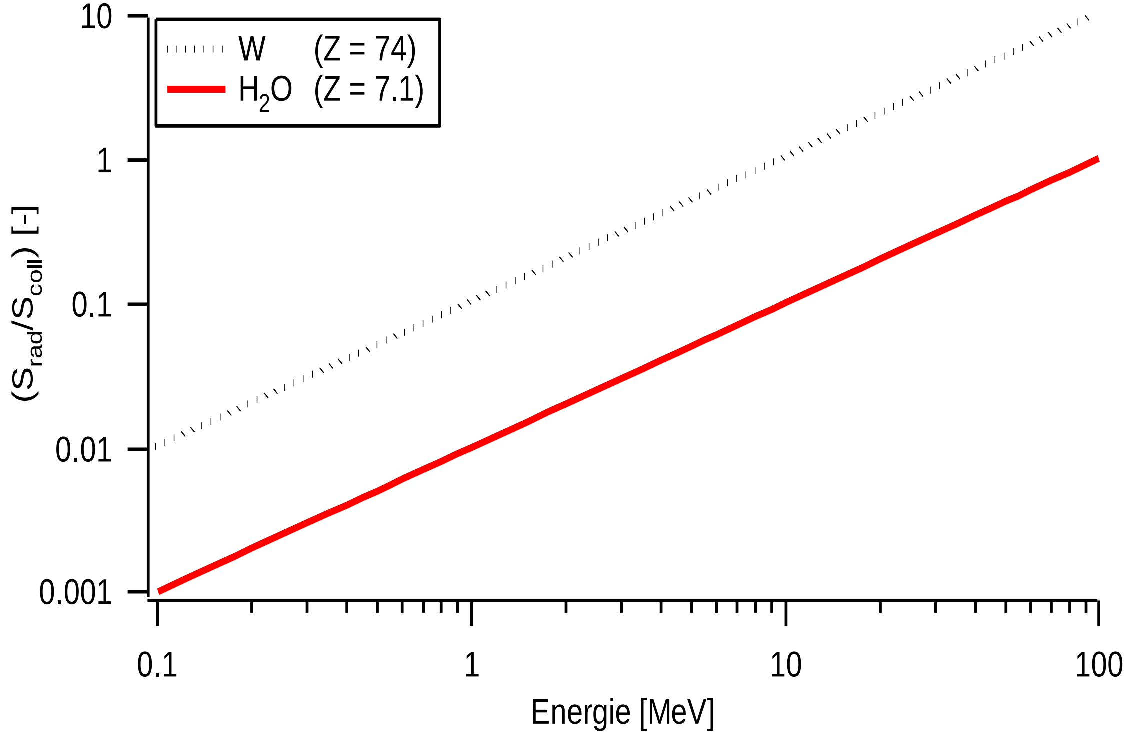


$$\frac{S_{rad}}{S_{coll}} \cong \frac{E[\text{MeV}]}{700} Z$$

- 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 components

Dependace on material (Z)



- ➢ Radiative process becomes dominant in tungsten from around 10 MeV
- ➢ This is why the conversion target (anode) of the X-ray tube is made of high Z material (W)

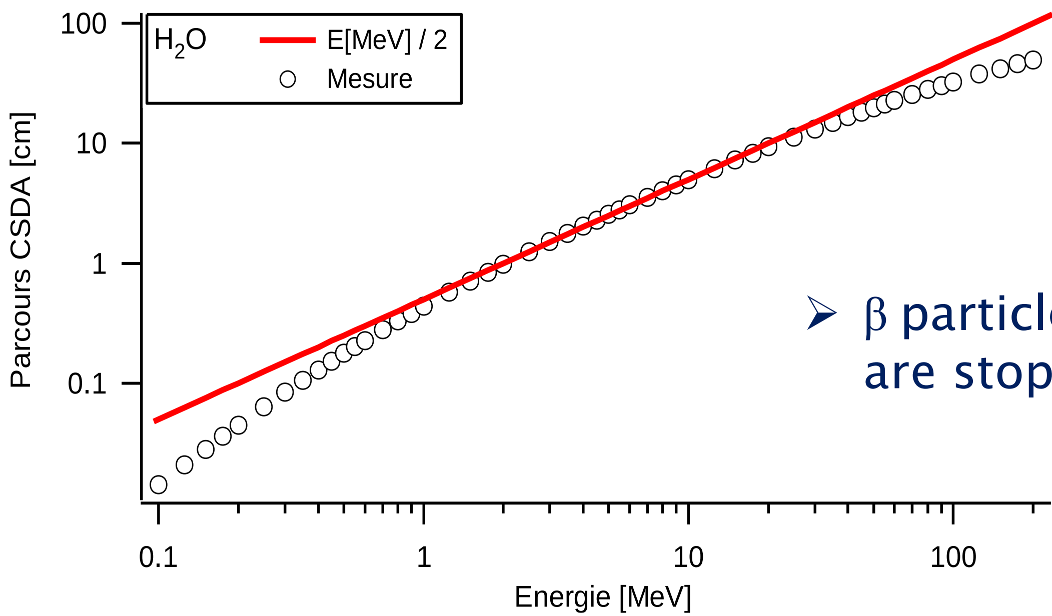
Radioactive decay

Q8: 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):

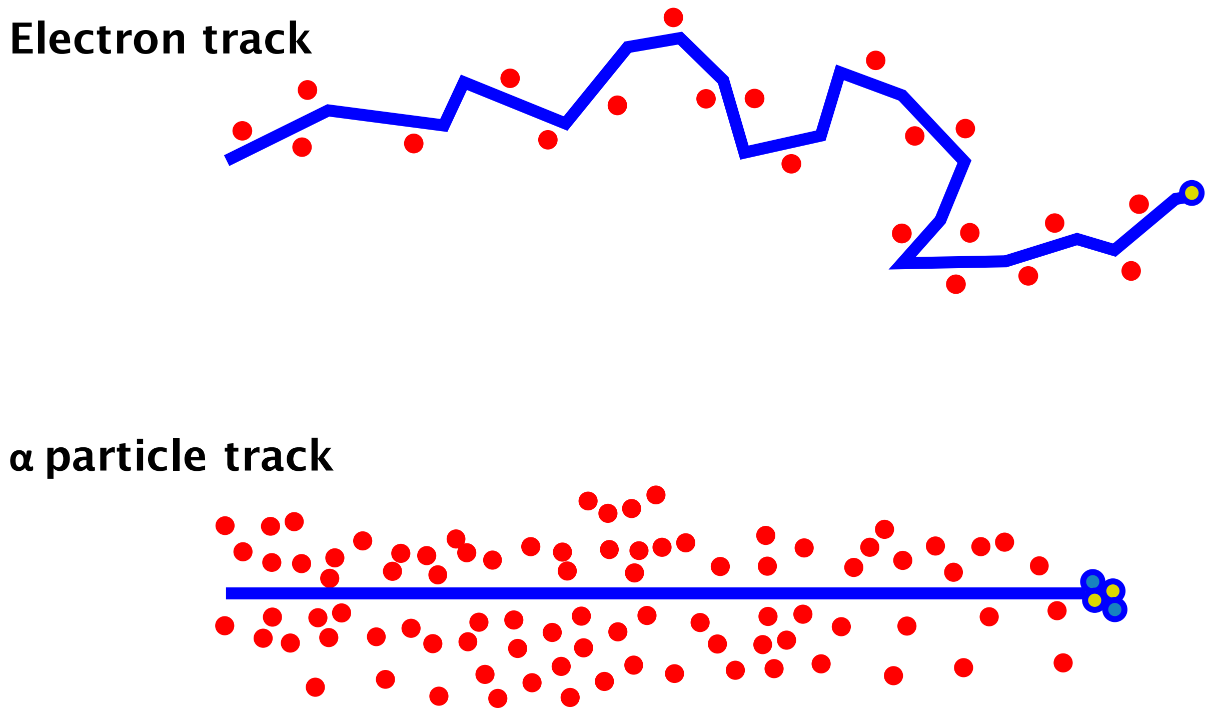
$$R_e\left[cm\right] \cong \frac{E\left[MeV\right]}{2}$$



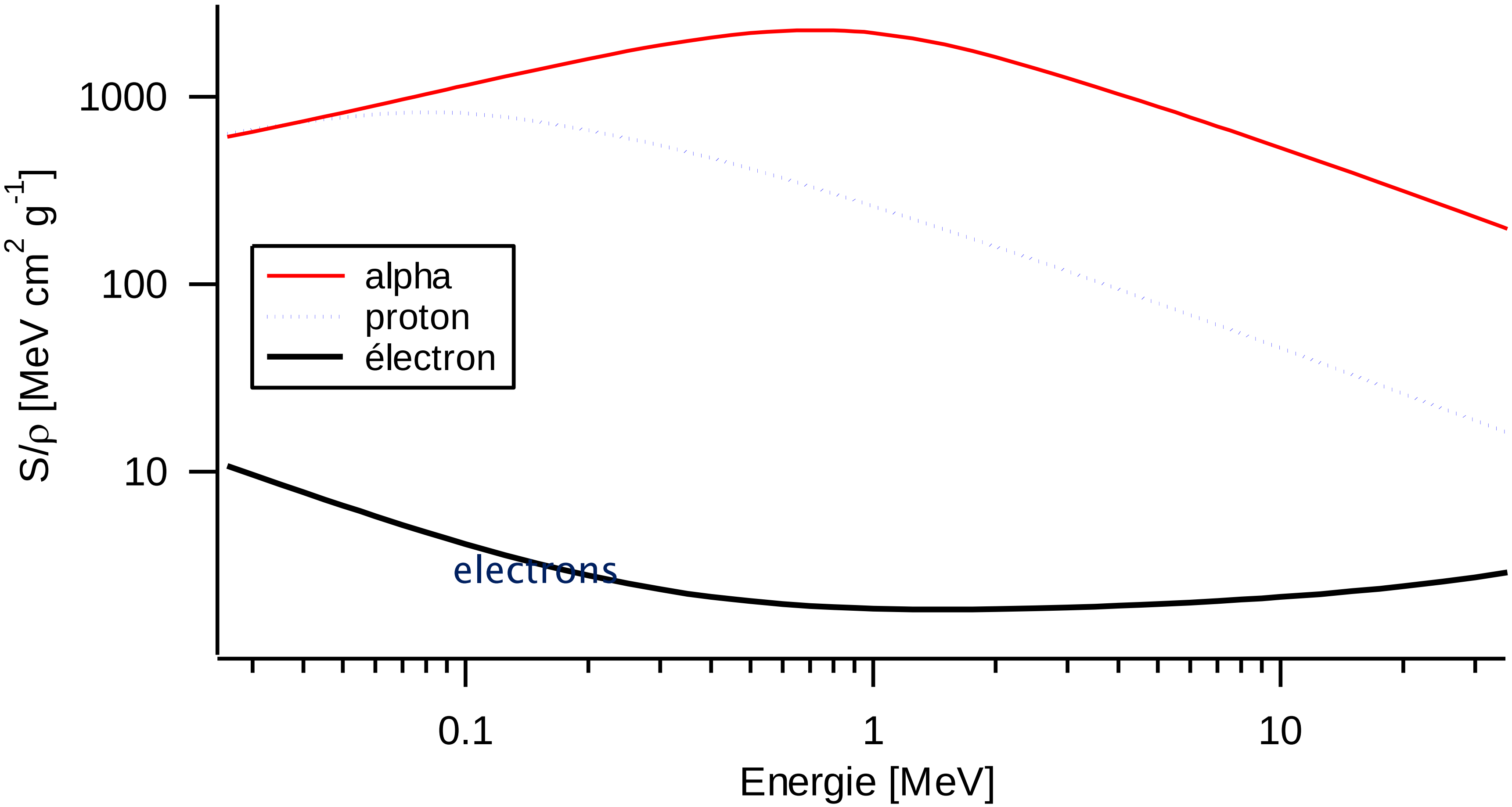
- β particles with max energy of 2 MeV are stopped by 1 cm of plexiglas

Heavy particles

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

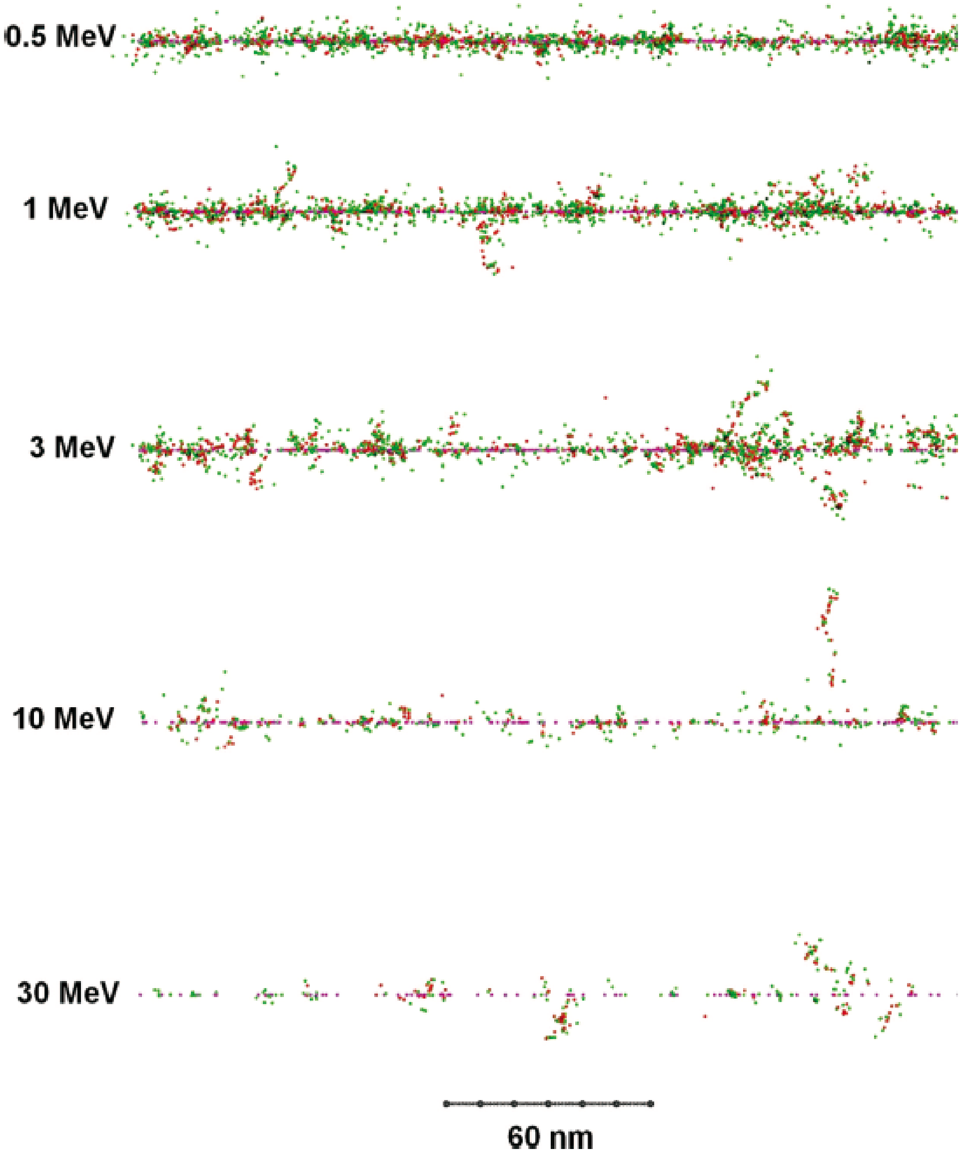


Stopping power of **heavy particles**



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

Alphas

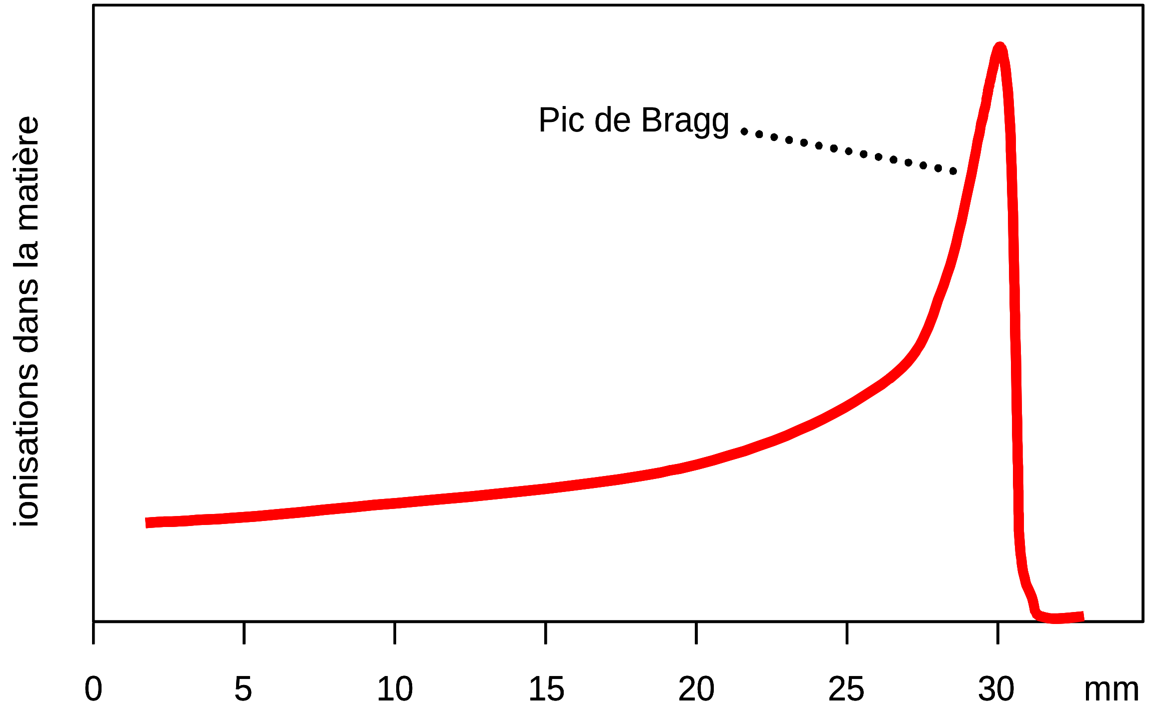


ICRU 86

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.

The Bragg peak

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

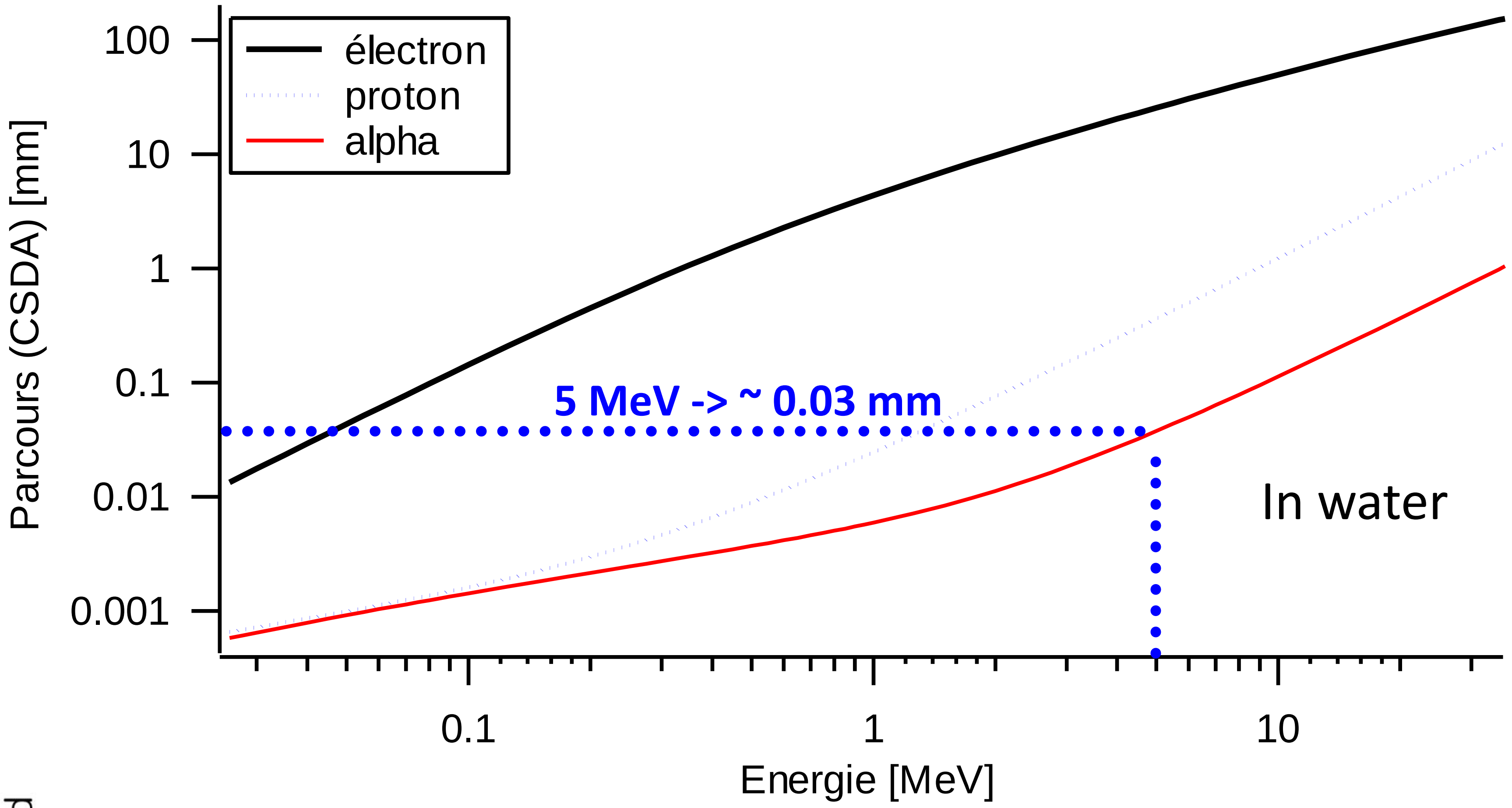


Example: 62 MeV proton beam in water

Radioactive decay

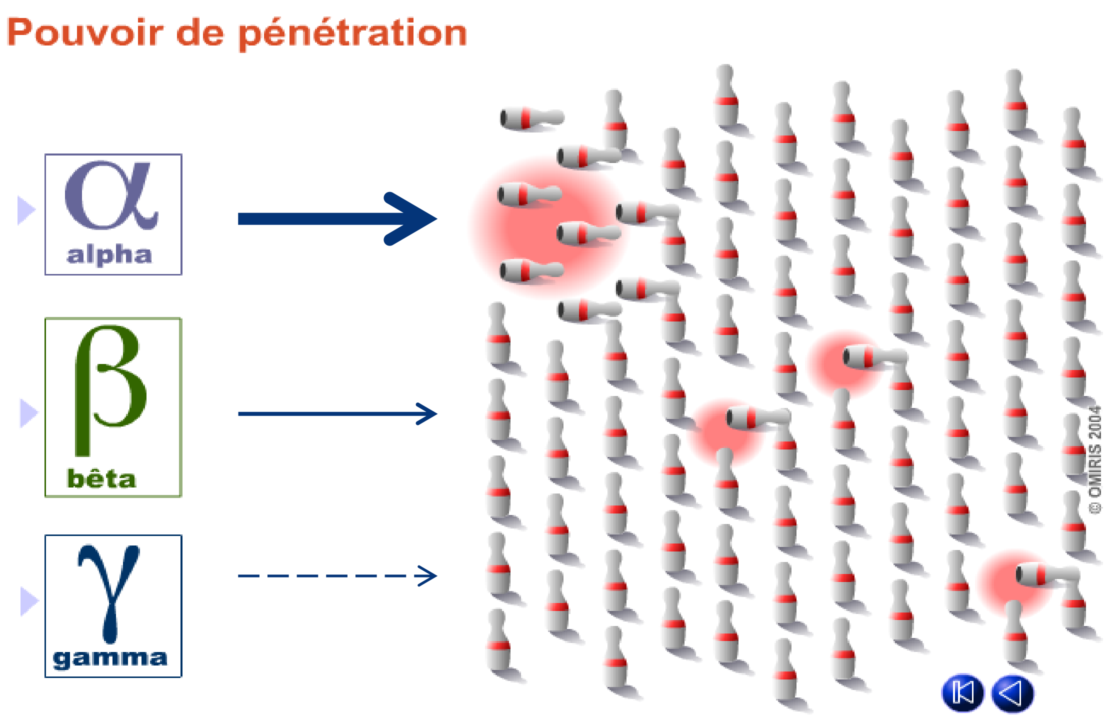
Q9: What is the advantage of using protons for tumor irradiation compared to X-rays?

Range of heavy particles in water



Radiation protection: Alpha particles

- The path of α particles emitted by a radioactive source (typical energy of about 5 MeV) in soft tissue is about 0.03 mm.
- This distance is very small and corresponds to the thin layer of dead cell on the surface of the skin. It is therefore relatively easy to protect from external α-source by using for example a simple sheet of paper or a glove.



Summary

− Charged particles are continually slowed as they pass through matter. They produce excitations and ionizations along their trace.

− Charged particles have a limited penetration depth in matter: their range. The heavier and more charged the particle, the smaller its range.

− For electrons:

- Trajectory is chaotic (zigzags).
- Stopping power through collision increases at low energy

− A positron (or beta plus particle) behaves like an electron. The difference can be seen at the end of the trajectory, when it annihilates itself with a surrounding electron to create two 511 keV photons.

− For heavy charged particles (mass greater or equal to the proton):

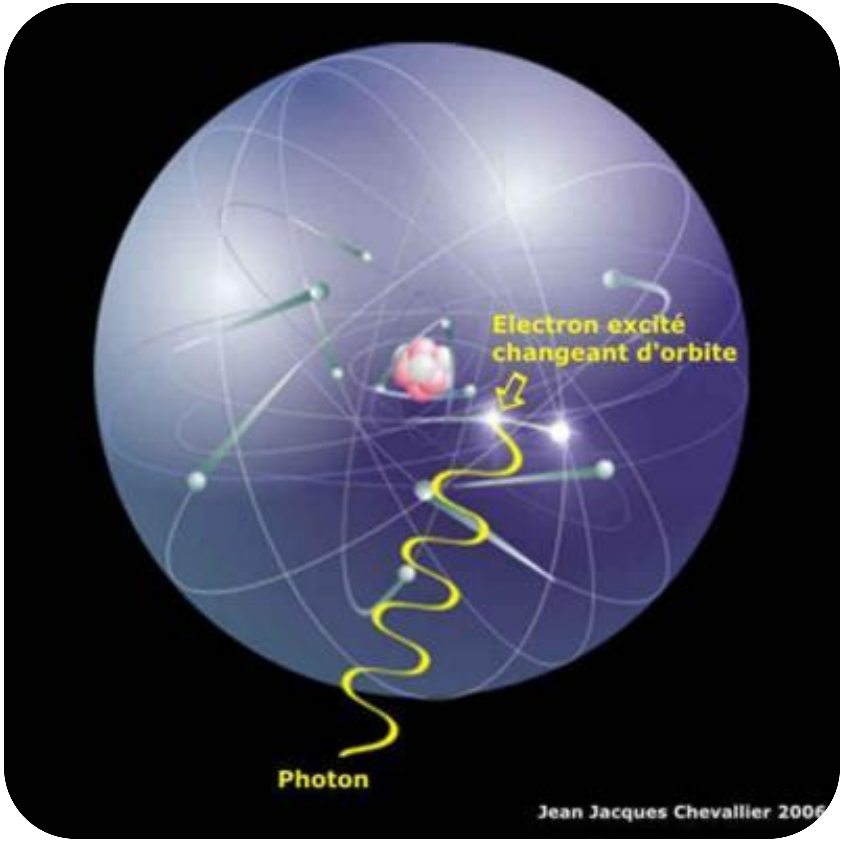
- The trajectory is straight.
- Braking is achieved essentially through collisions with surrounding electrons.
- Braking power increases at low energy (Bragg peak).

− The main differences between interactions of photons and heavy charged particles are:

- Photons are indirectly ionizing while charged particles are directly ionizing.
- Photons have a small number of reactions which free a great amount of energy while particles have many reactions which free a small amount of energy each time.

Interaction of **photons** with matter

- A photon penetrating the material can interact with the atomic electrons, nucleus or electromagnetic fields around the electrons or nucleus. During an interaction, the photon can "bounce" without loss of energy (elastic scattering), "bouncing" with loss of energy (inelastic scattering), or "disappearing" with loss of all its energy (absorption).



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.

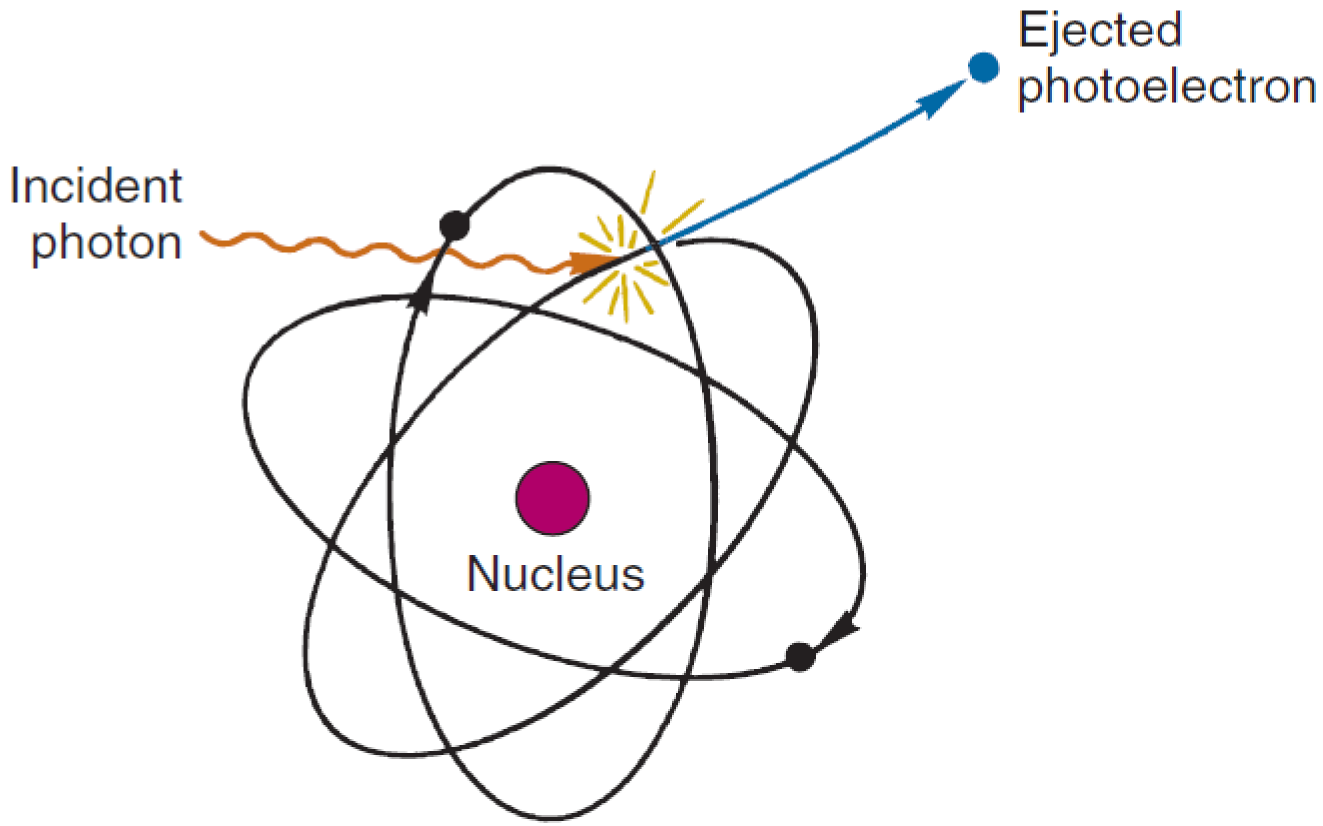
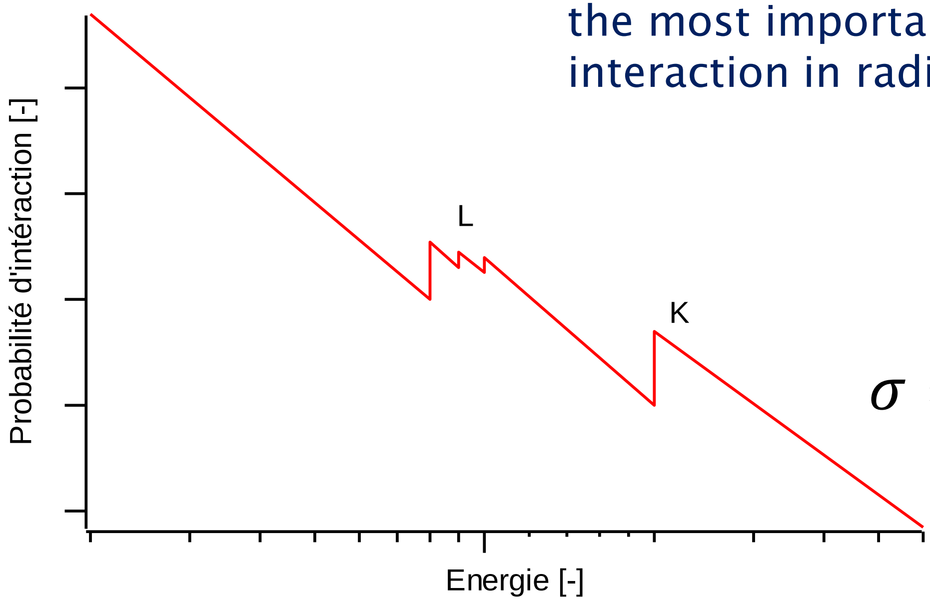


Image credit: Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

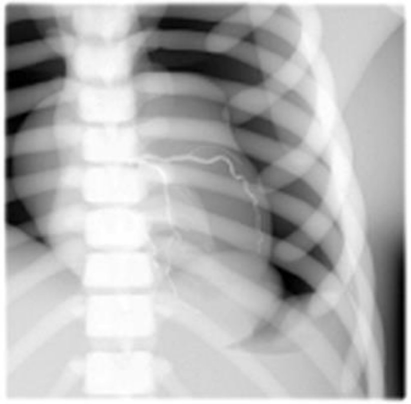
Interaction of photons with matter

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) is high. Typically, n is between 3 and 4.

Radioactive decay

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

Interaction of photons with matter

Compton effect

- The Compton effect (also called inelastic scattering): a photon collides with an electron.
- Part of the energy of the photon is transmitted to the electron. The rest of the energy appears as a scattered photon.

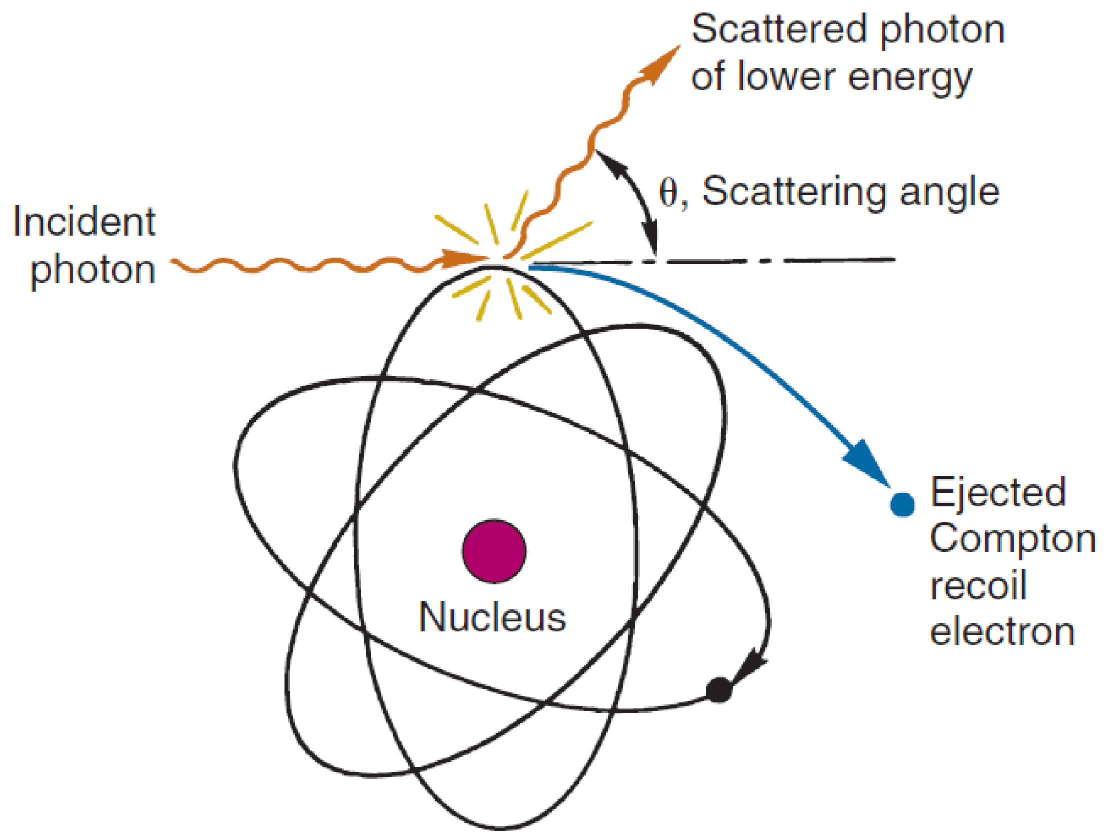
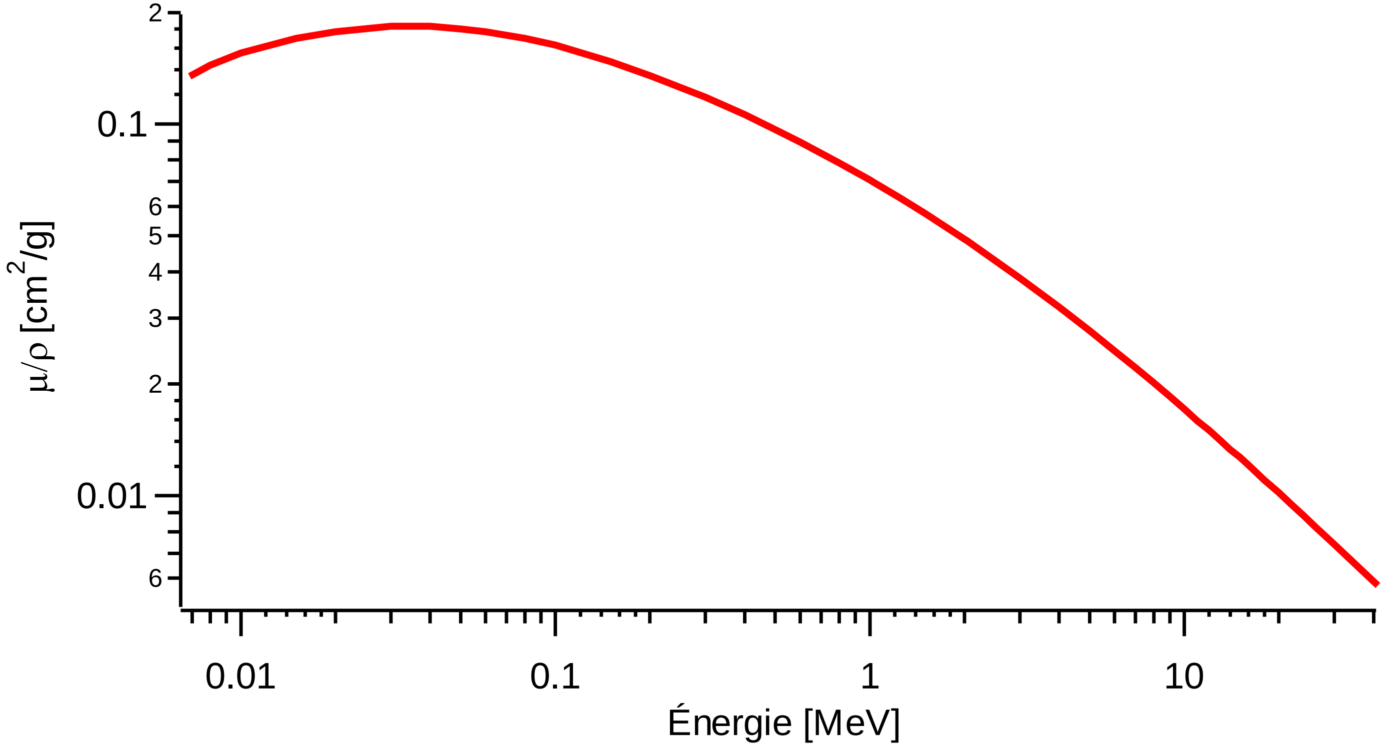


Image credit: Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

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

Probability of Compton effect in water



Interaction of photons with matter

Pair production

- Pair creation is an absorption of the photon by the electromagnetic field of the nucleus.
- It consists of the materialisation of the photon into an electron-positron pair

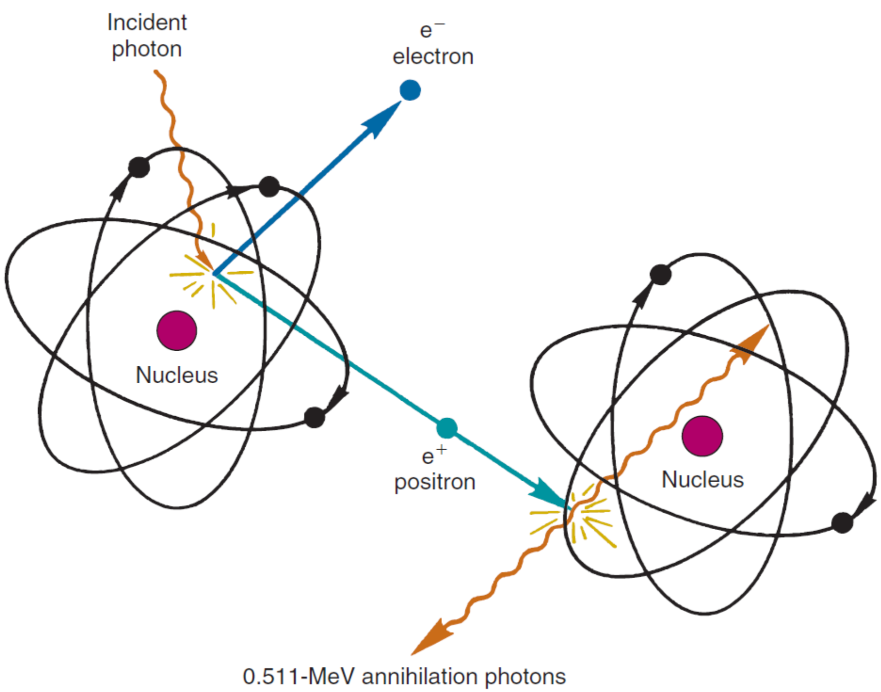


Image credit: Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

Interaction of photons with matter
Pair production

- The minimum energy required for the incident photon for a pair creation to be possible is 1022 keV (twice 511 keV).
- Once the threshold energy is exceeded, the interaction probability increases with energy

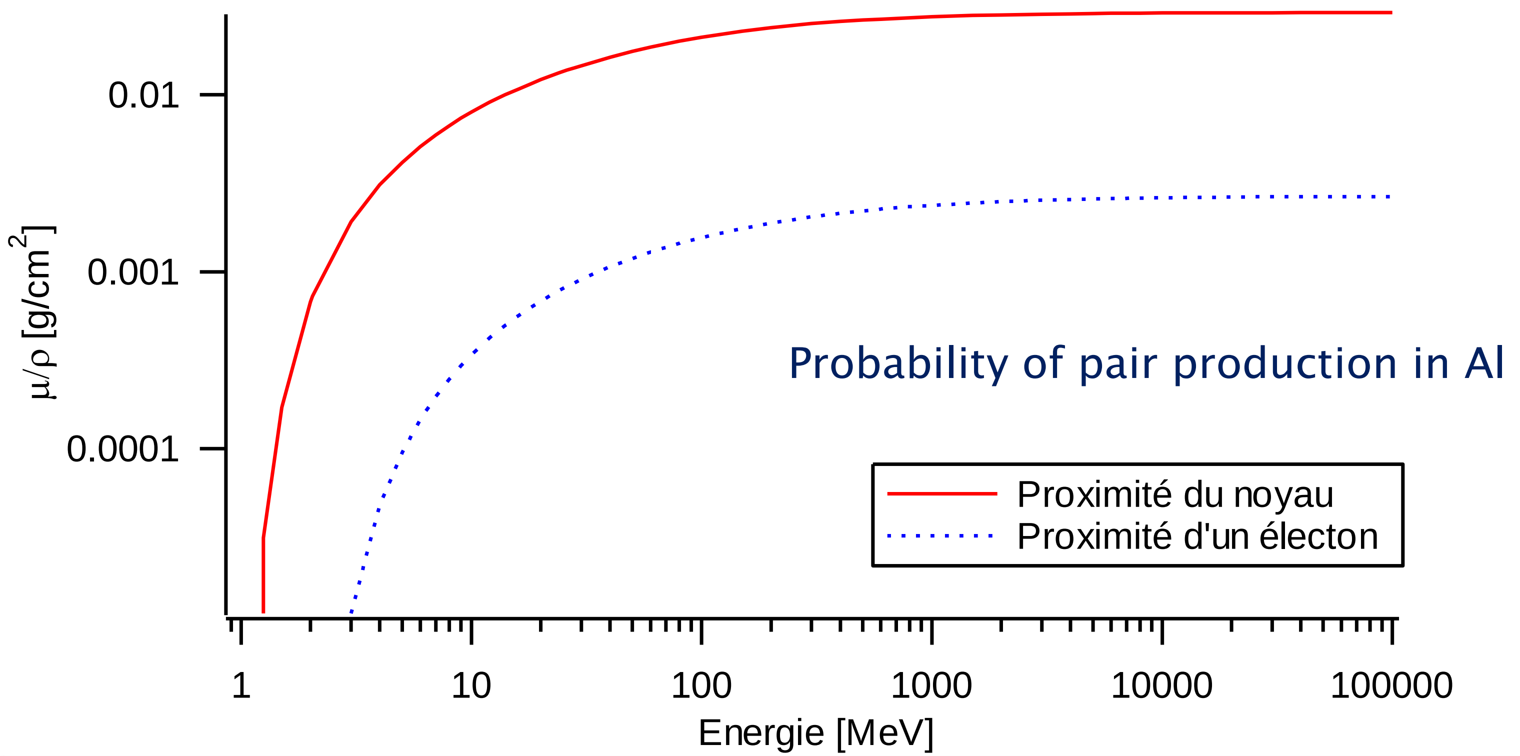


Image credit: Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

Interaction of photons with matter

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

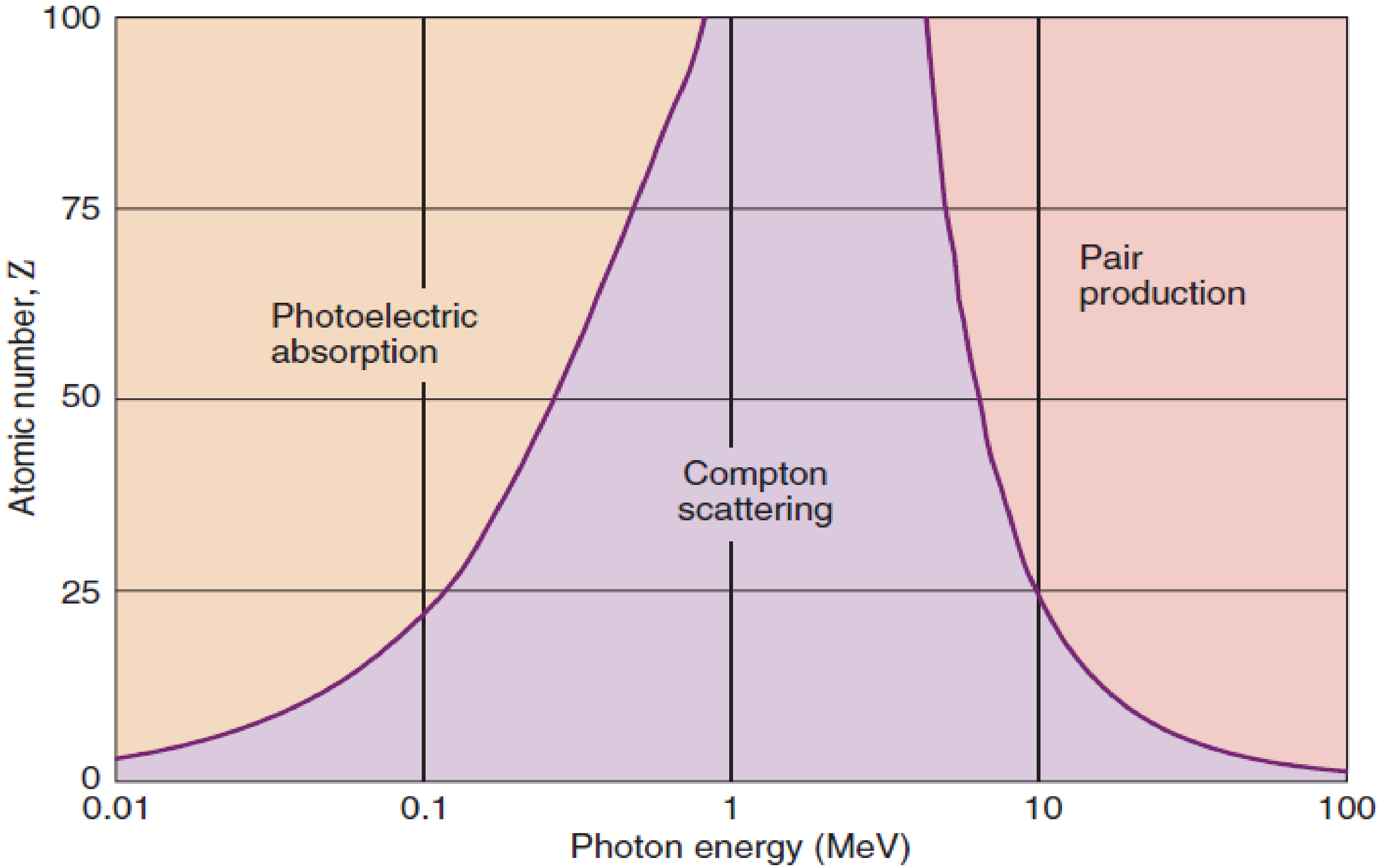
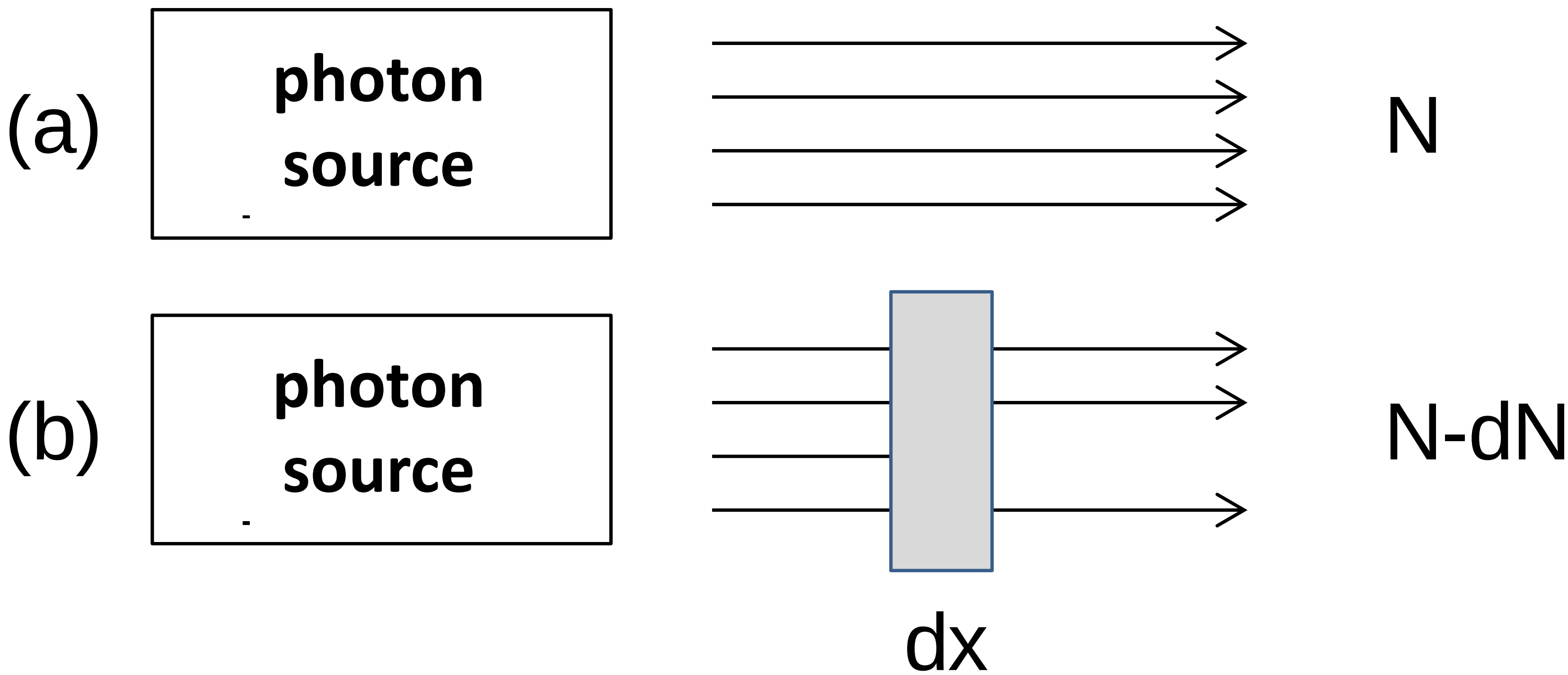


Image credit: Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

Photon beams attenuate, no range



Proportion interacting: **dN/N**

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

Photon attenuation: half value layer

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

$$\Downarrow$$

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

Summary

– The photoelectric effect involves the absorption of a photon by one of the atom's electrons. Its probability is maximum when the photon's energy is just enough to eject the electron outside its orbital. The interaction coefficient decreases with energy $(1/hv)^3$ and rapidly increases with the surrounding Z ($Z^{4.5}$).

– The Compton effect is the inelastic scattering of a photon on a "free" electron in which the electron absorbs a part of the photon's energy. The probability of the Compton effect decreases with the energy of the photon. It does not directly depend on the surrounding atomic number but is proportional to electron density.

– Pair creation consists in the materialization of an electron-positron pair when a photon disappears somewhere near the nucleus. The interaction has an energy threshold of 1022 keV. The probability of pair creation increases with the energy of the incident photon as well as with the atomic number of the material.

– The positron obtained through pair creation finishes by being slowed down and disintegrates with a surrounding electron, producing two 511 keV photons.

– The photoelectric effect occurs most often at low energy, the Compton effect prevails at medium energy (typically from 100 keV to 10 MeV) and pair creation prevails at high energy.

Summary of penetration capabilities of radiation emitted by radioactive materials