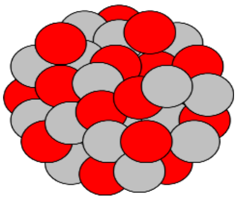
Chapter II: Radioactivity :

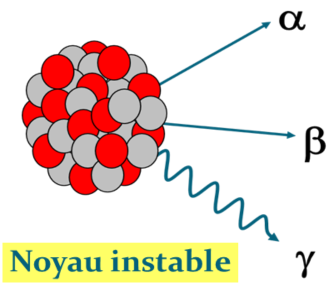
1. - Definition of radioactivity
2. - Natural radioactivity: main types of radiation
3. - Artificial radioactivity
4. - Law of radioactive decay
5. - Different types of nuclear reaction

II-1. Introduction

Radioactivity was not invented by humans. It is a natural phenomenon that was discovered at the end of the 19th century. In 1896, the French physicist Henri Becquerel was trying to determine if the rays emitted by fluorescent uranium salts were the same as the X-rays discovered in 1895 by the German physicist Wilhelm Roentgen. He believed that the uranium salts, after being excited by light, emitted these X-rays. To his surprise, he discovered in Paris in March 1896 that the photographic film had been exposed without being exposed to sunlight! He concluded that uranium emitted spontaneously and without being exhausted invisible radiation, different from X-rays. The phenomenon discovered is called radioactivity (from the Latin radius: ray). Following Henri Becquerel's work, Pierre and Marie Curie isolated polonium and radium in 1898, radioactive elements unknown in uranium ore. In nature, there are stable nuclei and unstable or radioactive nuclei.



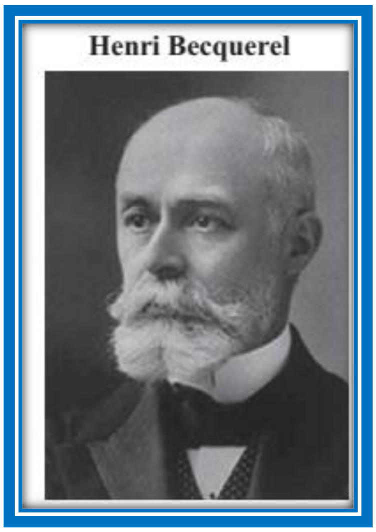
Stable nucleus

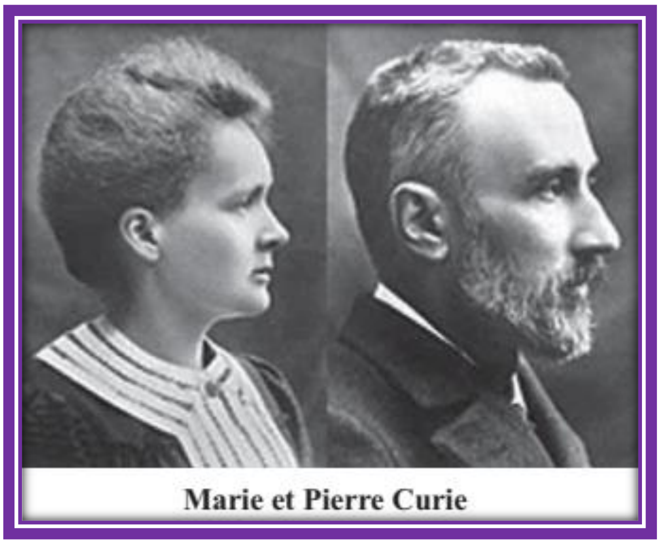


II-2. Definition

Radioactivity is the spontaneous emission of radiation (from the Latin radius, meaning ray) due to the instability of certain nuclei.

- In nature, there are stable and unstable nuclei.
- Lighter, unstable nuclei emit electrons or particles **β**
- The heaviest unstable nuclei emit helium nuclei $^{4}_{2}He^{2+}$ or **α** particles.
- The emission of **α** and **β** is often accompanied by the emission of energetic photons, which make up the γ radiation.
-  ***Pictogram indicating a radiation hazard. (☢)***


Henri Becquerel


Marie et Pierre Curie

II-2. Natural radioactivity:

In 1896, Henri Becquerel discovered that compounds of uranium emit a radiation that impresses photographic plates and ionizes the air. In 1898-1899, Pierre and Marie Curie isolated two elements more radioactive than uranium: polonium and radium. In 1900, Marie Curie suggested a hypothesis about radioactivity: "*Atoms undergo a metamorphosis and undergo transmutation with the emission of considerable energy.*"

- The natural radioactivity can be distinguished into three types of radiation: α, β, and γ.

II-2.1 α Radiation (helium) or α emission: These are positively charged helium nuclei ${}^{4}_{2}He^{2+}$ or hélium ions emitted at high speed during the transformation of a heavy nucleus (Z > 83) into a smaller nucleus. The radioactive element X transforms into another element Y, which is also radioactive or stable, followed by α emission.

Elément X → Elément Y + particule α

$${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + \alpha\ ({}^{4}_{2}He^{2+})$$

Examples:

$${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}He \qquad {}^{232}_{90}Th \longrightarrow {}^{228}_{88}Ra + \alpha$$

$${}^{210}_{84}Po \rightarrow {}^{206}_{82}Pb + {}^{4}_{2}He \qquad {}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + \alpha$$

- ✓ **α** particles are easily absorbed by metal plates.
- ✓ **α** particles are directly ionizing but not very penetrating.
- ✓ They are not dangerous to the skin.

II-2.1 β Radiation:

β particles are negatively charged with a very small mass close to that of an electron. These particles are emitted from nuclides with a high N/Z ratio. β particles can be negative electrons or positrons.

- ✓ Negative electrons are formed during the transformation of a neutron into a proton in the nucleus.

$${}^{1}_{0}n \longrightarrow {}^{1}_{1}p + {}^{0}_{-1}e\ (\beta^-) + {}^{0}_{0}\nu \text{ (neutrino)}$$

negative electron (e- negatively charged)

- ✓ Positrons are formed during the transformation of a proton into a neutron in the nucleus.
- ✓ ${}^{1}_{1}p \longrightarrow {}^{1}_{0}n + {}^{0}_{1}e\ (\beta^+) + {}^{0}_{0}\nu$ (neutrino) Positon (positively charged anti-electron)

In β- emission: Z increases by one unit.

In β+ emission: Z decreases by one unit.

$${}^{A}_{Z}X \longrightarrow {}_{Z+1}^{A}Y + {}^{0}_{-1}e\ (\beta^-) + {}^{0}_{0}\nu \text{ (neutrino)}$$

$${}^{A}_{Z}X \longrightarrow {}_{Z-1}^{A}Y + {}^{0}_{1}e\ (\beta^+) + {}^{0}_{0}\nu \text{ (neutrino)}$$

- They are more penetrating but less ionizing than alpha particles.
- They penetrate the skin to a depth of a few millimeters. They are dangerous to the skin.

Exemples

- ${}^{214}_{82}Pb \longrightarrow {}^{214}_{83}Bi + {}^{0}_{-1}e\ (\beta^-) + {}^{0}_{0}\nu$ (neutrino)
- ${}^{22}_{11}Na \longrightarrow {}^{22}_{10}Ne + {}^{0}_{1}e\ (\beta^+) + {}^{0}_{0}\nu$ (neutrino)

- ➢ A human body contains about 20 milligrams of ${}^{40}_{19}K$, a natural beta radioactive element.
- ➢ Thus, a human body produces about 340 million beta decays per day, naturally!

$${}^{40}_{19}K \longrightarrow {}^{40}_{20}Ca + {}^{0}_{-1}e\ (\beta^-) \quad 89{,}3\ \%$$

$$\longrightarrow {}^{40}_{18}Ar + {}^{0}_{+1}e\ (\beta^+) \quad 10{,}7\ \%$$

Soddy's Laws:

Radioactive reactions obey the two principles of conservation.

Law of Conservation of Mass: $\sum_i A_i$ (reactants) $= \sum_i A_i$ (products)

Law of Conservation of Charge: $\sum_i Z_i$ (reactants) $= \sum_i Z_i$ (products)

- ➢ Complete the following reaction

$${}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + \dots\dots\dots$$

$${}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{A}_{Z}X$$

Solution.

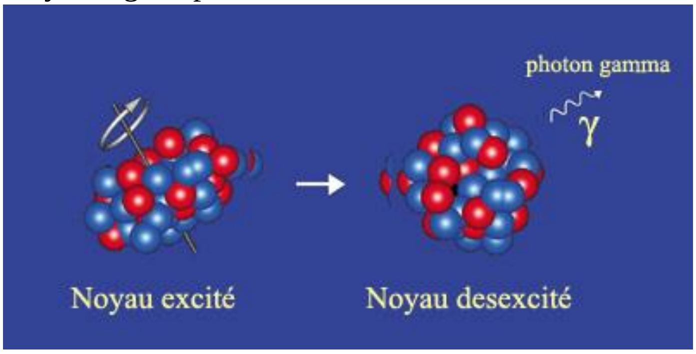
A : 238 = 234 + x A = 4 ${}^{A}_{Z}X = {}^{4}_{2}He^{2+} = \alpha$

Z: 92 = 90 + y Z = 2

- $^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{A}_{Z}X \Rightarrow \quad ^{A}_{Z}X = ^{239}_{92}X = ^{239}_{92}U$

II-2.3 Gamma radiation γ

- The emission of alpha α and beta β particles is often accompanied by an electromagnetic radiation of neutral charge and very short wavelength (λ < 1 A°) of the same nature as X-rays or light, called gamma rays γ.
- Gamma rays are due to the fact that the rays formed by radioactive decay are often in an excited state and tend to lose this energy to reach a stable state from an energetic point of view.
  Their nature is similar to photons, the only difference being in the energy they carry, as they are very energetic photons.

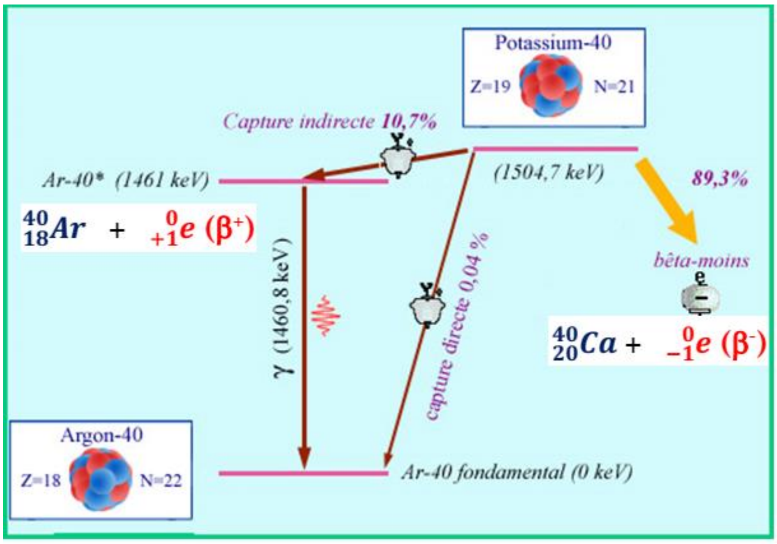


- The emission of gamma γ rays does not change either Z or A, but it reduces the atomic mass by an amount $\Delta m = \frac{h.v}{c^2}$

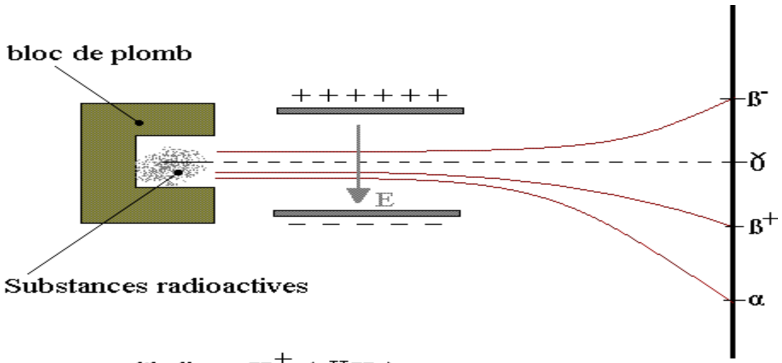
They are not directly ionizing, but they are very penetrating.
Natural radioactivity is spontaneous and is called natural because radioactive nuclei are found in a natural state.
Example:

$^{137}_{56}Ba^{*} \longrightarrow ^{137}_{56}Ba + \gamma$
Barium Barium
Unstable Stable

Example:

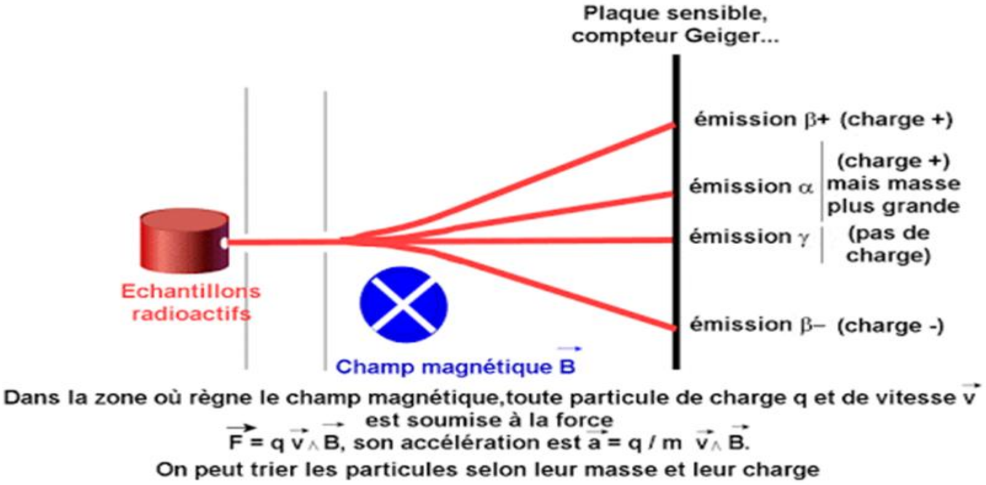


Action of an electric field $\vec{E}$



α : noyau d'helium He^{+} ($^{H}_{2}He$)
ß+ : position ou positon $^{0}_{+1}e$
ß- : électron ou position $^{0}_{-1}e$

The action of a magnetic field $\vec{B}$



II-3. Characteristics of radiation

- The action of electric and magnetic fields deflects **α** and **β**.
- **γ** is not deflected in the two fields.
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  The study of deflection has shown that:

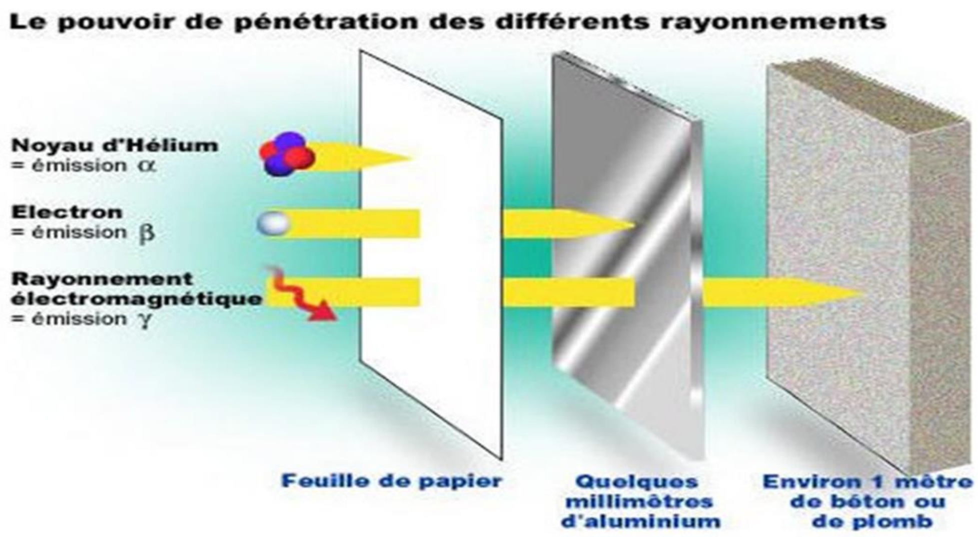
1) **α** is a beam of positive particles

2) **β** is a beam of negative particles with a mass less than that of **α**.

The other characteristic is the penetrating power through objects.

1. A sheet of paper is enough to block alpha particles.
2. **Beta (β)** particles have a penetrating power 100 times greater than that of **alpha (α)** radiation.
3. **Beta (β)** particles can be blocked by a thickness of 0.35 mm of Pb or by an aluminum plate of a few millimeters.
4. The penetrating power of **gamma (γ)** radiation is very high.
5. To block **gamma(γ)** radiation, a thickness of 1 m of Pb or concrete is required.
6. **gamma(γ)** is a radiation 10 to 30 times more dangerous than **β** or **α**.

The penetrating power of different types of radiation



Radioactive reactions

There are 2 types of radioactive reactions: natural and artificial.

1- Natural radioactive reaction:

A ⟶ **B** + *radiation*

During a decay, the formed nucleus B can be radioactive, generating another unstable nucleus and so on.

A ⟶ **B** + *radiation*

↘ ⟶ **C** + *radiation*

↘ ⟶ **D** + *radiation*

↘ ……… ⟶ **E** *(stable compound)*

There is a whole series of nuclei that appear one after the other, together constituting a radioactive family.

These families are mainly derived from heavy nuclei presented as follows:

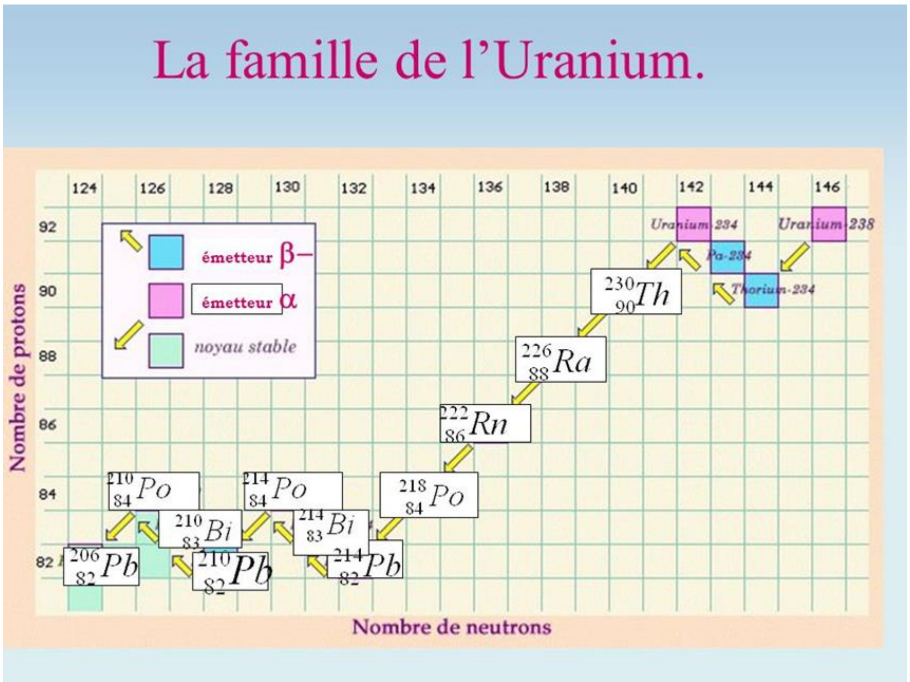
1- Uranium family whose mass number **A = 4n+2** (n: natural integer).

2- Actino-uranium family **A = 4n+3**

3- Thorium family **A = 4n**,

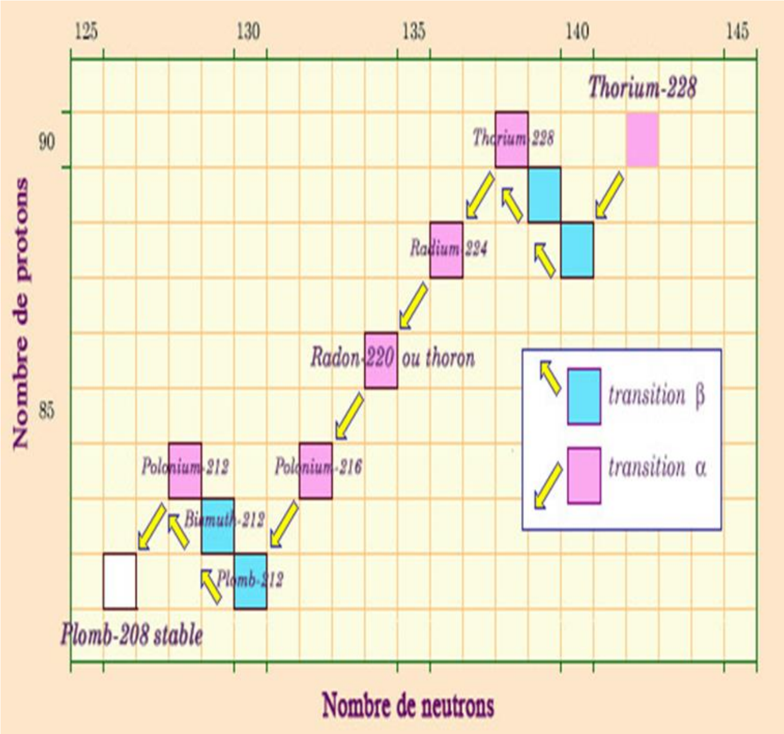
All these families lead to the stable isotope of Lead (Pb).

Uranium 238 family



Élément chimique	Radioactivité	Demi-vie
Plutonium 242	Radioactivité alpha	373 000 ans
Uranium 238	Radioactivité alpha	4,4688 milliards d'années
Thorium 234	Radioactivité bêta	24 jours
Protactinium 234	Radioactivité bêta	1,2 minutes
Uranium 234	Radioactivité alpha	b245 000 ans
Thorium 230	Radioactivité alpha	75 000 ans
Radium 226	Radioactivité alpha	1602 ans
Radon 222	Radioactivité alpha	3,8 jours
Polonium 218	Radioactivité alpha	3 minutes
Plomb 214	Radioactivité bêta	27 minutes
Bismuth 214	Radioactivité bêta	20 minutes
Polonium 214	Radioactivité alpha	160 µ-secondes
Plomb 210	Radioactivité bêta	22,3 ans
Bismuth 210	Radioactivité bêta	5 jours
Polonium 210	Radioactivité alpha	138,376 jours
Plomb 206	Stable	

Thorium family



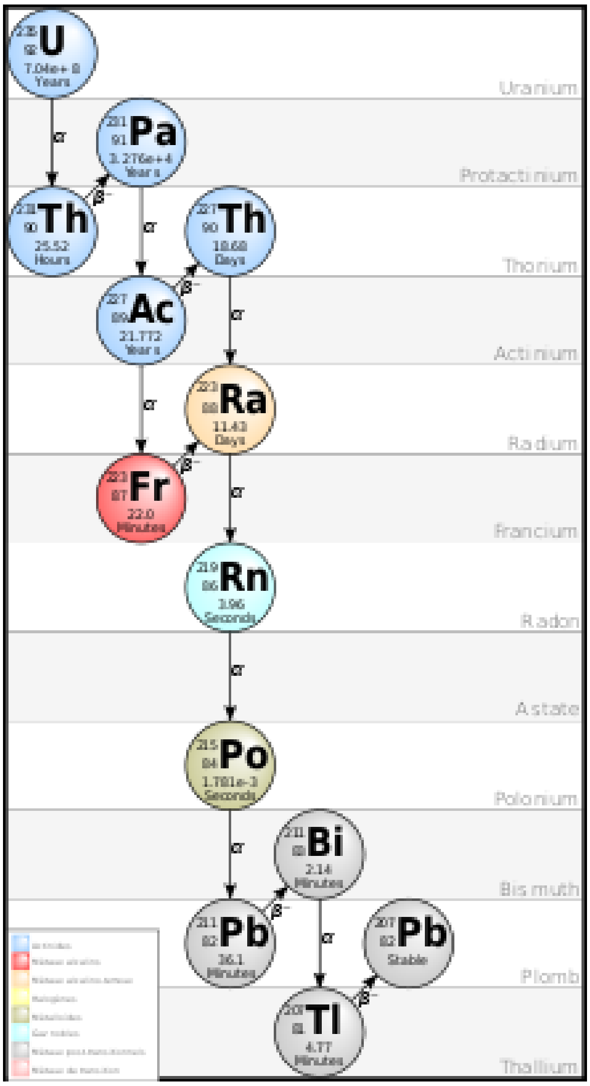
The filiation of thorium:

Natural thorium (thorium-232) is, like uranium-238, the origin of a series of radioactive elements that ends with a stable lead isotope, lead-208. The filiation of thorium, like that of uranium, includes a gaseous element, radon-220, called "thoron" for historical reasons. This radioactive emanation is less dangerous than uranium radon. Since the period of thoron is only 55 seconds, the gas hardly has time to escape from the rock.

Élément chimique	Rayonnement	Demi-vie
Plutonium 244	Radioactivité alpha	80 millions d'années
Uranium 240	Radioactivité bêta	14,1 heures
Neptunium 240	Radioactivité bêta	62 minutes
Plutonium 240	Radioactivité alpha	6.560 années
Uranium 236	Radioactivité alpha	23,42 millions d'années
Thorium 232	Radioactivité alpha	14,05 millions d'années
Radium 228	Radioactivité bêta	5,75 années
Actinium 228	Radioactivité bêta	6,15 heures
Thorium 228	Radioactivité alpha	1,9 années
Radium 224	Radioactivité alpha	3,63 jours
Radon 220	Radioactivité alpha	55,6 secondes
Polonium 216	Radioactivité alpha	0,145 secondes
Plomb 212	Radioactivité bêta	10,64 heures
Bismuth 212	Deux voies de désintégration : **Radioactivité bêta** (probabilité de 64,06 %). **Radioactivité alpha** (probabilité de 35,94 %)	60,55 minutes

β− : Polonium 212	Radioactivité alpha	0,3 µ-secondes
α : Thallium 208	Radioactivité bêta	3,053 minutes
Plomb 208	Stable	

Uranium 235 family



Famille de l'uranium 235

Élément chimique	Radioactivité	Demi-vie
Plutonium 239	Radioactivité alpha	24 110 années
Uranium 235	Radioactivité alpha	7 milliards d'années
Thorium 231	Radioactivité bêta	25,2 h
Protactinium 231	Radioactivité alpha	32 700 ans
Actinium 227	Radioactivité bêta	21,8 années
Thorium 227	Radioactivité alpha	18,72 jours
Radium 223	Radioactivité alpha	11,43 jours
Radon 219	Radioactivité alpha	3,96 secondes
Polonium 215	Radioactivité alpha	1,78 millisecondes
Plomb 211	Radioactivité bêta	36,1 minutes
Bismuth 211	Radioactivité alpha	2,15 minutes
Thallium 207	Radioactivité bêta	4,77 minutes
Plomb 207	Stable